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NEXT GENERATION AIRPORT SURVEILLANCE RADAR (ASR-())) DEFINITION STUDY



June 1979

Final Report

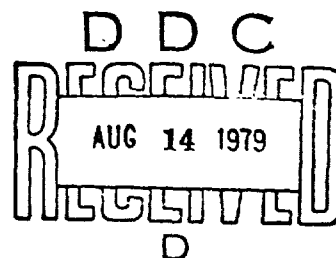
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16. Abstract A study group was convened in the Summer of 1974 by the Federal Aviation Administration (FAA) to define the characteristics of the next generation airport surveillance radar (ASR). This was designated as the ASR-(). The study group was comprised of representatives from MIT Lincoln Laboratory, the Johns Hopkins University Applied Physics Laboratory, MITRE, NAFEC, AAF, AAT, ASP, AEM and ARD. The operational requirements developed for the ASR-() include coverage on a small aircraft (one square meter radar cross section) out to 40 nautical miles; up to 15,000 feet altitude; at elevation angles of 0.3 to 30 degrees; in an environment of precipitation clutter, ground clutter, angel clutter, and anomalous propagation; and with a resolution commensurate with a separation standard of 2 nautical miles at a range of 30 nautical miles. Reliability, maintainability, and availability should be equal to that of the ASR-7 and ASR-8. Using the operational requirements, candidate radar systems were defined at four frequencies; VHF (420-450 MHz), L-band (1250-1350 MHz), S-band (2700-2900 MHz) and 5'-band (3500-3700 MHz). The recommended system is the L-band system which has the following characteristics: azimuth beamwidth of 2.25 degrees, PRF of 1100-1360 pps, data rate of 4 sec., instrumented range of 60 nmi and a pulse width of 1.0 usec. 4			
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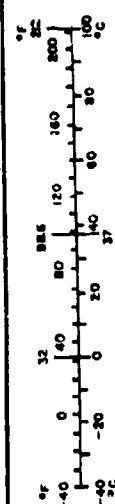
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	meters	m
yd	yards	0.9	kilometers	km
mi	miles	1.6		
AREA				
sq in	square inches	6.5	square centimeters	cm ²
sq ft	square feet	0.09	square meters	m ²
sq yd	square yards	0.8	square meters	m ²
sq mi	square miles	2.6	square kilometers	km ²
ac	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
teaspoon	teaspoons	5	milliliters	ml
fluid ounce	fluid ounces	30	milliliters	ml
cup	cup	0.24	liters	l
quart	quart	0.95	liters	l
gallon	gallon	3.8	liters	l
cu ft	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

When You Know	Multiply by	To Find	Symbol
LENGTH			
millimeters	0.04	inches	in
centimeters	0.4	inches	in
meters	3.3	feet	ft
meters	1.1	yd	yd
kilometers	0.6	miles	mi
AREA			
square centimeters	0.16	square inches	in ²
square meters	1.2	square yards	yd ²
square kilometers	0.4	square miles	mi ²
hectares (10,000 m ²)	2.5	acres	ac
MASS (weight)			
grams	0.005	ounces	oz
kilograms	2.2	pounds	lb
tonnes (1000 kg)	1.1	short tons	ton
VOLUME			
milliliters	0.03	fluid ounces	fl oz
liters	1.1	quarts	qt
liters	0.26	gallons	gal
cubic meters	35	cubic feet	ft ³
cubic meters	1.1	cubic yards	yd ³
TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature
°F			°C



*1 in = 2.54 exactly. For other exact conversions and more detail tables, see NIST Metric Publ. 286, Units of Weight and Measure, Price \$2.25, SO Catalog No. C110-286.

EXECUTIVE SUMMARY

A study group was convened in the summer of 1977 by the FAA to define two new radar systems. The group was comprised of representatives from MIT Lincoln Laboratory, John Hopkins University Applied Physics Laboratory, MITRE, NAFEC, AAF, AAT, ASP, AEM and ARD. One of these radars was designated as the ASR-() and it was envisioned that this system would be the next generation ASR. The other radar is designated as the Short Range Terminal Radar (SRTR) which is designed for use at high traffic density VFR airports which do not presently qualify for an ASR. This report documents the study group's deliberations, conclusions and recommendations concerning the ASR-().

The operational requirements to be met by the ASR-() are that they system must be able to maintain surveillance on a small aircraft, (i.e. one square meter radar cross section, Swerling Case I fluctuation characteristics) under the following conditions:

- a. ranges of 1 to 40 nautical miles
- b. altitudes to 15,000 feet above ground level
- c. elevation angles of 0.3 degrees to 30 degrees
- d. in representative land, weather and anomalous propagation environments
- e. with resolution commensurate with a reduced separation standard of two nautical miles at a range of thirty nautical miles
- f. four second data rate
- g. with reliability, maintainability and availability that is at least as good as the ASR-7 and ASR-8

Using the operational requirements listed above, candidate radar systems were developed using frequency bands of interest. Parameters were optimized considering system performance and cost. The frequencies considered were:

- a. VHF (420 - 450 MHz)
- b. L-band (1250 - 1350 MHz)
- c. S-band (2700 - 2900 MHz)
- d. S'-band (3500 - 3700 MHz)

The recommended ASR-() system is an L-band (1250 - 1350 MHz) system with the following characteristics:

azimuth beamwidth	2.25 degrees
PRF	1100 - 1360 PPS
data rate	4 sec
instrumented range	60 nmi
pulse width	1.0 usec
signal processing	MTD

The establishment cost for this system which includes radar system cost, test equipment, provisioning and inspection, regional installation costs, radar buildings and shipment and installation is \$787,000. These funding estimates are in 1974 dollars and should be adjusted to reflect current costs.

Subsequent to the completion of the study group's activities, a much greater emphasis has been placed by the FAA on the detection of hazardous weather. This requirement may dictate that the ASR-() be an S-band system.

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Allentown, Pennsylvania Airport

Wilkes-Barre, Pennsylvania Airport

New York Common IFR Room

NAFEC

Texas Instruments (ASR-8 Division)

Southwest Regional Headquarters; Ft. Worth, Texas

FAA Depot; Oklahoma City, Oklahoma

Oklahoma City Flight Service Station

1.0 INTRODUCTION

New FAA ATC automation concepts, plans for discrete address beacons, advances in digital radar signal processing, and new surveillance radar antenna technology have pointed to a need for FAA surveillance radars which employ this new technology to meet automation requirements. With this need in mind, FAA ARD authorized ⁽¹⁾ a Radar Study Group, organized as shown in Figure 1.1, and made up of radar specialists from within the FAA, and from Johns Hopkins Applied Physics Laboratory, M.I.T. Lincoln Laboratory, and MITRE, to examine the requirements for future terminal area surveillance radars. As shown in the figure, two separate working groups were spawned by the Group, one to study Short Range Terminal Radars and the other to study longer range surveillance radars similar to the present FAA ASR-type radar. The latter subgroup has commonly been referred to as the "ASR-() Subcommittee."

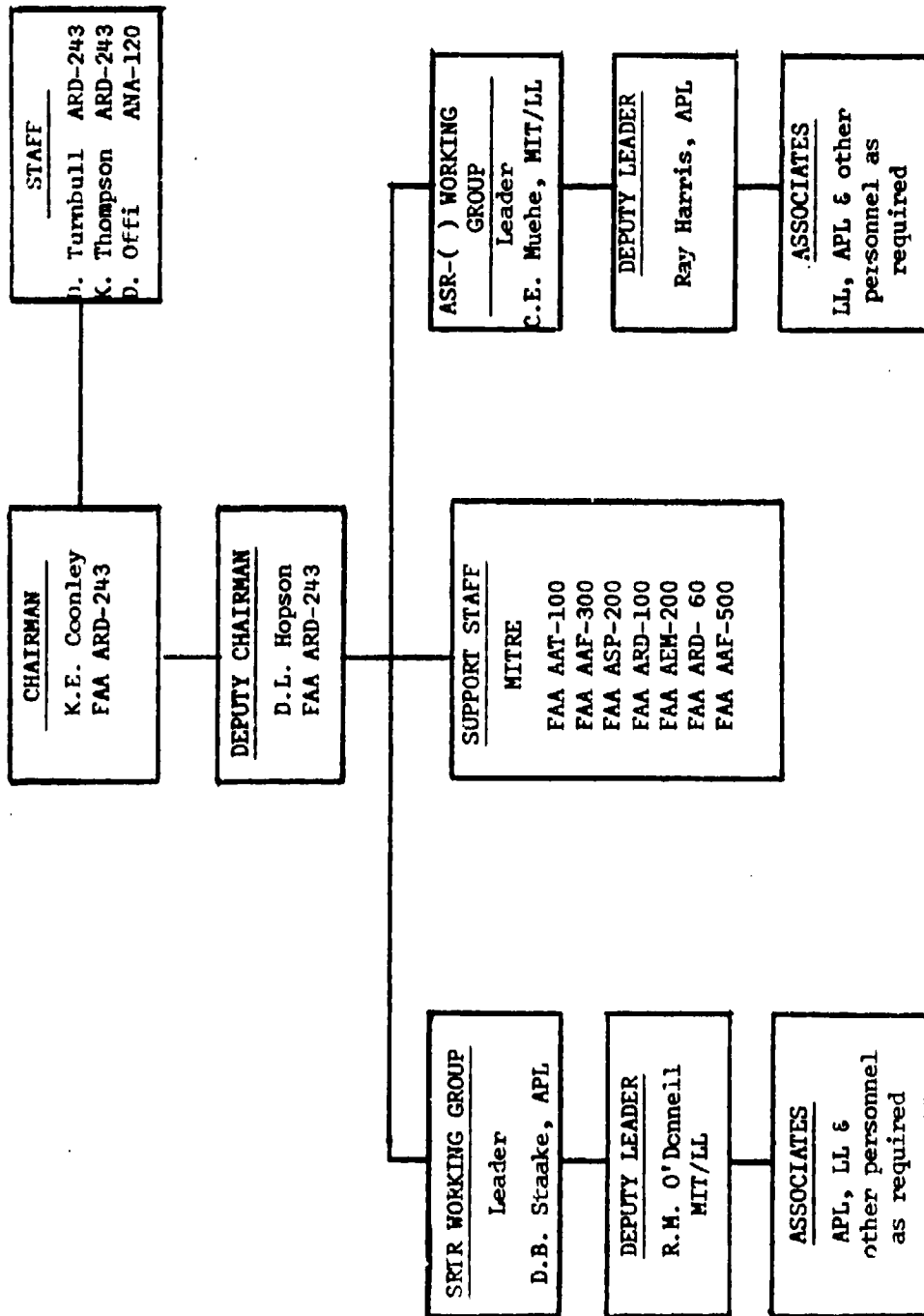
This report records the investigations, conclusions, and recommendations of the ASR-() subcommittee; the SRTR Subcommittee has reported separately. Both subgroups held many meetings with their FAA counterparts and traveled to several operational field installations for purposes of familiarization and assessment of current surveillance radar operational problems.

1.1 Purpose of ASR-() Study

The ASR-() radar study was authorized for the purpose of determining; (1) whether a new airport surveillance radar matching recent advances in ATC automation and beacon systems is necessary, (2) if so, what the operational requirements for such a radar should be, emphasizing requirements which would lead to the elimination of present ASR operational deficiencies and to the extension of the usefulness of the ASR in ATC operations, and (3) what such an ASR should be like in detail.

1.2 Desirable ASR-() Characteristics

General knowledge of recent surveillance radar and beacon developments permits certain desirable attributes of any successor - ASR to be stated at the outset. These are outlined below in preview of later sections of this report where rationale, theory, and field experience supporting these choices are presented in detail.



RADAR STUDY GROUP
ORGANIZATIONAL CHART

FIGURE 1.1

ASR-() TEAM MEMBERS

Kenneth Coonley	FAA/ARD-243
Dan Hopson*	FAA/ARD-243
Donald Turnbull	FAA/ARD-243
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Gerald Carp*	FAA/AEM-200
Kenneth Thompson	FAA/ARD-243
R.A. Ramos	FAA/ARD-120
Charles Kohlhausen*	FAA/AAF-320
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Dominick Offi	FAA/ANA-120
Steven Zaidman	FAA/ASP-100
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Arthur Williamson	APL/JHU
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Frank Castella	APL/JHU
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Robert O'Donnell	MIT/LL
John Beusch	MIT/LL
Jean-Claude Sureau	MIT/LL

*Not with the noted organization at date of publishing.

The FAA successor airport surveillance radar ("ASR-()") should:

- 1.2.1 Make use of existing real estate (sites), towers, antenna drives, antennas, etc. to the maximum extent possible, and where not possible permit smooth transition away from them.

This goal strongly favors L-band as the operating frequency for the recommended ASR-() because:

- Desirable antenna patterns may be obtained at L-Band using antennas equal in size to antennas planned for future beacon interrogators (DABS). These may then be added in back-to-back fashion on existing towers and pedestals.
- L-Band is close in frequency to the frequencies used by beacon interrogators and hence ground multipath siting considerations are nearly identical and common, in most cases presently available sites may be used.
- Transmitter power requirements are much smaller at L-Band than at S-Band resulting in lower transmitter cost and higher reliability. (Lower transmitter power requirements follow from lower waveguide losses, elimination of losses due to use of circular polarization for rain rejection and use of a larger antenna).

- 1.2.2 Capitalize on the energy-saving, improved coverage, and optimum clutter-rejection features of advanced antenna design.

This goal favors the use of a so-called "zoom antenna" for the recommended ASR-() because:

- The zoom antenna will provide vertical coverage comparable to a radar with cosecant-squared vertical pattern at no increase in transmitter power.
- The zoom antenna provides optimum rejection of moving clutter/rain, bird flocks, etc.

- 1.2.3 Include demonstrated advances in high reliability, cost-effective, digital signal processing.

This goal would be satisfied by employing digital processing techniques demonstrated in the Lincoln Laboratory "Moving Target Detector (MTD)" processing. This processing in combination with non-saturating, coherent receiver design:

- Eliminates undesired moving targets (not already removed by STC and the zoom antenna), ground vehicles and second time around aircraft.

- Eliminates mutual radar interference. (Using these techniques it is estimated that several thousand radars could be operated simultaneously in a 50 MHz band in the Continental United States).

1.3 Roles of the ASR-()

The services to be provided by the ASR-() are listed below. Note that many contribute directly to air safety and that several functions, although provided nominally by present day ASR's, are services which are of value in proportion to the reliability and continuity of the radar data provided in clutter, low altitude, etc. conditions.

1.3.1 Beacon System Augmentation

An ATC beacon system can track all aircraft with properly operating transponders. It can automatically supply vital altitude and identity information. However, beacon transponders do fail, and typical large terminal control areas such as New York do experience numerous unequipped intruders daily, even though beacons are mandatory within all Terminal Control Areas. An ASR is expected to pick up these intruders, provide for the safe handling of the other equipped aircraft, and to fill in for the faulty beacon. The radar is thus used to monitor beacon performance and to detect beacon faults.

Due to the location of the beacon antenna on many aircraft, beacon replies are occasionally lost. This may happen for many successive scans, as when the aircraft is in a turn with the wing shielding the beacon antenna from the interrogator. During this interval, the radar is again expected to make up for the loss of beacon replies.

Because all aircraft are required to be beacon equipped in the upper airspace, it is believed by many that primary radar coverage of the enroute airspace (above about 15,000 ft.) will be unnecessary in the not too distant future. The implementation of such a scheme calls for the positive assurance that each aircraft entering the upper airspace is equipped with a properly operating DABS or ATCRBS transponder. By monitoring all aircraft as they take-off and depart from the terminal area, low altitude terminal radar could be used to provide assurance that each aircraft is equipped with a properly operating transponder. Another role of the radar is to provide, in cases where the radar and

antennas are mounted back-to-back, position reports from a given aircraft at twice the data rate, alternately on beacon and radar. Such an arrangement allows earlier acquisition of aircraft and improves track quality.

1.3.2 Mapping of Hazardous Regions

Radar can be used to map regions where flying may be hazardous due to the presence of hail or extreme turbulence. An improved ASR could be used to keep the controller abreast of the true location of the intense weather cells. These cells often move through the terminal area rapidly, and the presently available data provided by meteorological radar is often tens of minutes old, so is of little use to the controller.

Another hazard which can be warned against is heavy concentrations of birds. The probability of bird damage increases precipitously during the bird migration season, especially when climbing or descending through the typical altitude of migrating bird flocks, a few thousand feet above ground level. A typical calculation ⁽²⁾ shows that for a landing operation, the probability of bird damage goes from one part in 100,000 in periods of average risk to one part in 5,000 during periods of heavy bird migration. The probability is one in 500 of striking a bird while flying for one hour at the same altitude as the birds during a typical migration season at night. The pilot, warned of the presence of the birds could fly so as to minimize his exposure.

1.3.3 Service During Emergency Situations

Radar can be valuable in emergency situations faced by the controller. If the ground beacon interrogator fails, radar information can be used to fill in so as not to completely disrupt the air traffic control system. With the proposed ASR-() capable of automatic acquisition and tracking of all aircraft within its coverage the only missing information will be height and identity. This can be obtained by voice information from the pilot. Once identity is established, the ASR-() will track the aircraft on the controller's display as if it were being tracked by the beacon system.

Another situation where emergency radar service is called for is in the guidance of VFR aircraft. An aircraft not equipped for IFR will take off under VFR conditions and either due to inexperience or because the weather suddenly closes in, become lost. Radar could locate the lost aircraft. In this regard, the combination of radar and VHF/UHF direction finding offer a powerful combination to quickly locate and identify a lost aircraft. When the pilot calls in, the direction finder points to his aircraft and it is then associated with its radar report. In an automated system, such as ARTS-III, a label could then be affixed to the lost aircraft.

1.3.4 Providing Information to Other Systems

The whole ATC system is gradually evolving and many suggestions have been made as to its form and functioning 10 or 20 years from now. One important suggestion is that sensor outputs be used cooperatively. A control facility would receive aircraft position reports from all sensors which have any coverage within the control area. When overlapping sensor coverage is available, the reports will be merged so as to present the controller with the best information available. A further role of the radar, therefore, would be to provide clear, clean reports on each aircraft, particularly those not equipped with beacons, and to eliminate any unwanted reports due to false alarms, bird flocks or ground vehicles.

Elimination of the requirement to cover aircraft above 15,000 ft. poses a problem since, at present, the enroute radars provide inputs to the air defense system. In the event that the use of the enroute radars is discontinued by the FAA, we assume that where necessary, operation would be taken over by the Air Force. We believe that saddling the ASR-() with the long range, high altitude detection function would lead to requirements which are too severe. The digitized output of the radar should, however, be readily available over narrow-band telephone lines to any qualified user. We believe that the excellent low altitude performance which will become available will be of great interest to other branches of the Government particularly those charged with the tasks of reducing smuggling operations and eliminating unlawful drug traffic in border areas.

2.0 OPERATIONAL REQUIREMENTS

The first task of the ASR-() subcommittee was to generate a set of requirements for a surveillance radar which would meet the operational needs of a major air terminal, and which could be built and maintained economically.

Assessment of operational needs included discussions with key personnel at the New York Common IFR Room, the Fort Worth Region, the FAA Academy, and the ARTS-III test bed at NAFEC. Discrete Address Beacon System (DABS) documentation was reviewed and analyzed to ascertain the probable role of the ASR-() for the DABS backup mission. Contributions were also received from Study Group members associated with the FAA, including the Air Traffic Service, the Airways Facilities Service, the Office of Systems Engineering Management, NAFEC, and from personnel of SRDS, Terminal Automation, Radar, Aviation Weather and Frequency Management sections. Inputs were also reviewed from equipment manufacturers and Study Group members from MITRE, MIT Lincoln Laboratory and the Applied Physics Laboratory who have been active in related FAA programs. Detailed reference to all documents reviewed is given under References at the end of this report.

The sections below outline the ASR-() requirements generated by the process and the rationale leading to their selection. In summary, it was concluded that the ASR-() should be capable of maintaining reliable surveillance on small general aviation aircraft (i.e., a one square meter fluctuating target) under the following conditions:

- a. At ranges of 1 to 40 nautical miles
- b. At altitudes to 15,000 feet above ground level
- c. At elevation angles of 0.3° to 30°
- d. In representative land, weather, and anomalous propagation environments
- e. With resolution commensurate with a reduced separation standard of two nautical miles at a range of thirty nautical miles
- f. With a four second data rate
- g. With reliability, maintainability, and availability that is at least as good as the ASR-7 and ASR-8

Furthermore, while the primary external interface of the ASR-() is expected to be with the Discrete Access Beacon System, it should also be capable of interfacing directly with the ARTS-III systems at sites where DABS is not installed.

2.1 Coverage and Siting

2.1.1 Coverage

Coverage is the volume defined in terms of range, azimuth, and elevation angle or altitude within which a radar can provide useful information on the smallest aircraft of interest, in this case, a small general aviation aircraft.

2.1.2 Detection Range Coverage: 1 to 40 nautical miles

A one square meter Rayleigh-fluctuating target at L- and S- band is an appropriate model for a small general aviation aircraft.* In Appendix A it is shown that a single-scan probability of detection of 0.75 with a false target report rate of one per hour is adequate for specifying the maximum performance range of the ASR-(). At this range, the radar must be capable of providing reliable surveillance, i.e., full air traffic control services on all aircraft in the required coverage volume.

In most cases examined by the Radar Study group, a range of thirty nautical miles appeared sufficient. In some cases, handovers to other facilities occurred at greater ranges, but these procedures did not represent situations where full air traffic control services were essential.

Forty nautical miles was chosen for the ASR-() detection range requirement to provide for flexibility in allocating air traffic control services in major terminal control areas, to facilitate metering

*Since small, single-engine aircraft are the most difficult to detect, the FAA, seeking assurance that this target representation is accurate, contracted the Air Force's RATSCAT facility to measure the backscatter characteristics of several small aircraft as a function of aspect angle, frequency, and polarization. Their results are presented in Appendix A.

and spacing at busy terminals, and to permit multisensor sharing of surveillance data between nearby sites. Virtually all useful ARTS-III multisensor candidate sites are within 40 miles of each other. ⁽³⁾

2.1.3 Azimuth Coverage: 360°

Virtually all sites require 360° azimuth coverage and no practical means of capitalizing on a reduction in azimuth coverage at particular sites can be found.

2.1.4 Altitude Coverage: 15,000 feet

As a terminal air traffic sensor, the ASR-() must provide surveillance up to altitudes where en-route airspace begins. The maximum transition altitude in current use is 14,500 feet. It is therefore sufficient that the ASR-() meet its performance requirements for small general aviation aircraft up to a maximum altitude of 15,000 feet out to the required 40 nautical mile detection range. With a fan-beam antenna pattern, larger aircraft will be detectable at higher altitudes. In addition, the 15,000 foot requirement must be tempered by the practicalities of providing radar coverage at very low and very high elevation angles, as discussed in the next section.

2.1.5 Elevation Angle Coverage: 0.3° to 30°

The ASR-7 and ASR-8 antenna elevation patterns are intended to provide elevation coverage up to a maximum of 30°. (When Sensitivity Time Control is used with a cosecant-squared antenna pattern, this maximum is not always met). The 30° coverage provides a cone of silence above the radar with a radius of about five miles at 15,000 feet altitude, three miles at 10,000, and one mile (the ASR-() minimum instrumented range) at 3,000 feet. This performance was judged sufficient for the ASR-().

At low elevation angles, requirements are set primarily by the need to handle traffic using satellite airports which lack radar facilities. However, as the required minimum elevation angle coverage decreases, line-of-sight considerations and ground lobing effects make radar detection more difficult. A minimum elevation angle of 0.3° was selected as a reasonable compromise. The resulting minimum altitude coverage is 2,200 feet at the required detection range of

40 miles, about 900 feet at 20 miles, and 600 feet at 15 miles, which is sufficient for handover to non-radar satellite airport towers.

The coverage requirements for the ASR-() are summarized in Figure 2-1. The solid lines outline the coverage over which full air traffic control services can be provided, and apply to a one square meter target. The corresponding coverage for five and ten square meter targets (representative of a small air carrier aircraft) is also shown, along with the maximum ASR-() instrumented range.

2.1.6 Siting

Radar coverage and siting are interrelated. If the radar is unable to adequately handle ground clutter and traffic, it is best to locate the radar as low as possible. This provides a relatively short radar horizon which acts to screen out low-altitude clutter but worsens coverage for low altitude aircraft. In addition, high-density terminals invariably have large buildings spotted about the airport grounds, and blind zones from these structures severely limit low-altitude surveillance. It is, therefore, important to design the ASR-() so that it is able to handle the increased clutter and radio frequency interference encountered in locations where a very high (e.g., 100 feet) antenna installation is feasible.

2.1.7 Instrumented Range: * 1 to 60 nautical miles

Minimum instrumented range is set by air traffic control procedures⁽⁴⁾ which require radar contact on departures within one mile of the runway. A minimum instrumented radar range of one mile or less permits the ASR-() to be placed at the end of a runway and still meet the one nautical mile departure rule requirement.

The ASR-() Maximum Instrumented Range requirement is related to the instrumented range of beacon systems which the ASR-() must operate.

*Instrumented range, as opposed to detection range, refers to a range which the radar is designed to display. Instrumented range is thus determined by system timing, not by the power-aperture product constraints or target characteristics.

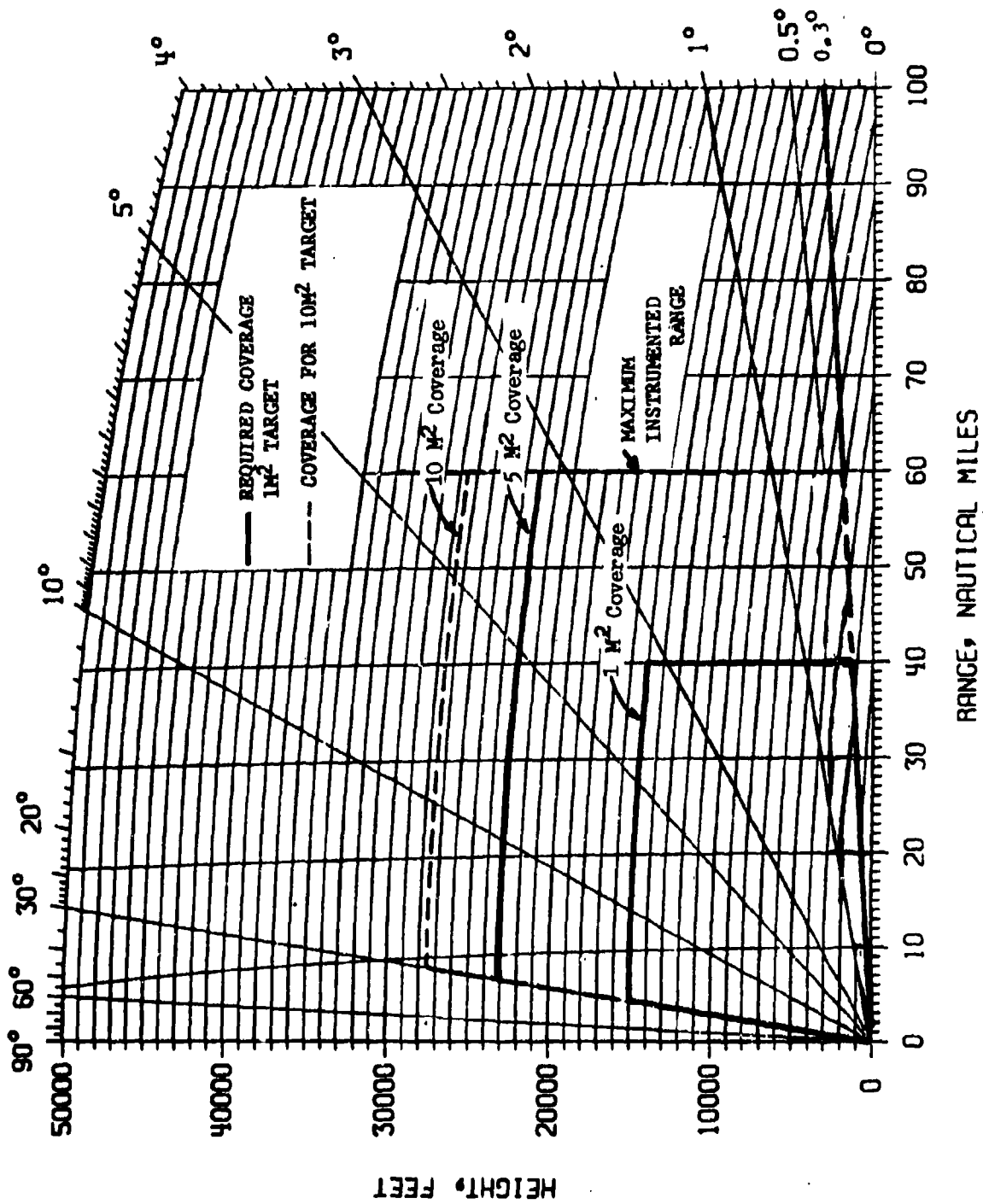


FIGURE 2-1 ASR-() COVERAGE REQUIREMENT

The ARTS-III instrumented range is 55 nautical miles. The Discrete Address Beacon System (DABS) has an instrumented range of 100 nautical miles, largely because DABS cost was not significantly affected by increasing range from 60 to 100 miles. Also, the larger value provides some opportunity for fail soft operation, in cases where a remote-site DABS provides overlapping surveillance information to a site at which DABS is temporarily inoperative. A maximum instrumented range of sixty nautical miles was chosen for the ASR-(). This permits the radar pulse repetition frequency to be high enough to provide good performance in clutter, is consistent with ARTS-III multisensor operation (where adjacent ARTS sites share surveillance data), and sacrifices little surveillance capability because aircraft at 100 miles and above 0.3° elevation angle must be above 9,700 feet in altitude. In the DABS backup role, ASR-() surveillance beyond sixty miles was not considered to be a cost-effective contribution since the remote DABS supplying overlapping coverage would also have an ASR-() for providing this back-up service.

2.1.8 Aircraft Speed

The current air speed limit for aircraft at altitudes of 10,000 feet and below is 250 knots (indicated). Converting to true airspeed and adding a 40 knot allowance for winds aloft, this translates into range rates of zero to 340 knots. This speed range represents the primary performance region for the ASR-() surveillance.

The lower limit of zero is not usually achievable with conventional MTI cancellers since the clutter notch is centered about zero, although propeller and jet engine modulation or large broadside radar cross sections may permit detection in some cases. Since transponder antenna masking often occurs when aircraft are in turns, and turning targets represent a difficult tracking problem, it is essential that the ASR-() be provided with the capability to detect range rates down to zero when the aircraft cross section is sufficiently larger than the competing clutter background to permit detection with reasonable false alarm rate control.

The upper limit of 340 knots applies to aircraft of primary interest for terminal air traffic control and is appropriate for optimizing radar performance. However, reasonable performance against subsonic aircraft above this speed must be maintained by the ASR-() since intermittent detections on such aircraft could produce troublesome short tracks as they transit the area. The Radar Study Group concluded that no specific requirement should be placed on the ASR-() to handle supersonic aircraft; it was assumed that special procedures would be used in the rare cases that such aircraft transit ASR-() coverage regions.

2.2 Operational Frequency Allocations

2.2.1 Candidate Frequency Bands

While many technical considerations apply to the choice of a good radar frequency for the ASR-(), the availability of a suitable frequency allocation in the desired band is often an overriding consideration. In order to provide safe and reliable air traffic control, it is necessary that the FAA be designated as the primary user in the frequency band of the ASR-(). At the present time, the FAA enjoys this status in the following bands:

- a) 2.7 - 2.9 GHz - (low S-band) for the present Airport Surveillance Radars (ASR)
- b) 1.30 - 1.35 GHz - (L-band) for the present Air Route Surveillance Radars (ARSR)
- c) 9.0 - 9.18 GHz - (X-band) for the discontinued FAA Precision Approach Radar (PAR)

An agreement between the FAA and the Office of Telecommunications Policy has established a fourth candidate, where aeronautical radionavigation and radiolocation have been assigned as co-equal services:

- d) 3.5 - 3.7 GHz - (high S-band), which is intended for future low cost terminal radar
- e) 1.25 - 1.30 GHz - (L-band) which is used by military radars and ARSR radars operated at FAA/military joint-use sites

A sixth band was considered because of several desirable radar detection attributes.

- f) 0.42 - 0.45 GHz - (UHF band) which is currently used for military radars

2.2.2 Selection of Frequencies for ASR-() Study

X-band was rejected because the clutter rejection and transmitter power required for the relatively long range ASR-() surveillance mission are not consistent with economical design at X-band.

The remainder of the bands listed in 2.2.1 represented viable candidate frequencies for the ASR-(), either because operation may possibly be dictated by precedent (e.g., the 2.7-2.9 and 3.5-3.7 GHz bands) or because of technical advantages.

In order to simplify the analysis, a single representative frequency was chosen for each band:

S_H : 3.6 GHz for high S-band

S_L : 2.8 GHz for low S-band

L: 1.3 GHz for L-band

UHF: 0.43 GHz for UHF

While 200 MHz of bandwidth is available at S_H and S_L , only 50 MHz is currently available for both ARSR and ASR-() radars at L-band. The military has confined their use to the 1.25 - 1.30 GHz band and this will continue into the foreseeable future. Thus only 50 MHz of bandwidth is currently available at L-band. However, there is some possibility that FAA priority can be established for peacetime use of the military frequencies to provide an operating bandwidth of 100 MHz at L-band.

At UHF, the process of securing FAA priority was estimated to require at least five years by FAA frequency management personnel. UHF was considered in the ASR-() study to determine if the benefits of operating at these frequencies would justify a request for permission to operate there.

2.3 Resolution

Resolution is defined as the minimum separation between two aircraft for which a radar can recognize both as distinct targets. Angular resolution is the resolvable spacing in angle for two aircraft in the same cell; range resolution is similarly defined for two aircraft at the same azimuth.

2.3.1 Angular Resolution

Angular resolution is a function of the radar beamwidth, the relative size (and signal-to-noise ratios) of the two aircraft, and the method of beamsplitting employed in the radar target data processing system. Figure 2.2 shows the relative received signal levels versus azimuth for two aircraft separated by 1.7 times the antenna beamwidth. For radar cross-section ratios of unity and one hundred, the signal overlaps occur at the -20 dB and -13 dB points, respectively. This was judged adequate for relating the required air traffic control separation standard to one-way half-power antenna beamwidth (θ).

Table 2-1 lists the three possible separation standards which the ASR-() may be required to meet. Separation Standard I is currently in use and II is a proposed reduction (1.5 miles out to 15 miles) that is currently being considered by air traffic control. A two mile separation standard has been proposed⁽⁵⁾ for future growth; Case III in Table 2-1 applies to the 2 mile standard at 30 and 40 miles. The table also shows the minimum azimuthal separation for each possible standard, and the beamwidths required for the ASR-() using the 1.7 θ criteria.

A maximum beamwidth of 2.24 $^{\circ}$ was chosen as a reasonable value for the ASR-(); this will meet standards I and II and will permit 2 mile separation out to 30 miles. Narrowing the beamwidth to 1.7 $^{\circ}$ to provide 2 mile separation at 40 miles was not considered desirable because:

- a) the narrower beamwidth provides 25% fewer returned pulses per beamwidth, which tends to render coherent signal processing less effective in handling clutter;
- b) radar return from distributed clutter is only 1.2 dB higher for the wider beamwidth
- c) antenna size is 25% smaller with the wider beamwidth.

Elevation resolution could provide the ASR-() with the ability to discriminate against land, weather, and angel clutter to provide more useful weather data, and to determine relative altitudes of aircraft when Mode C beacon data is not available. However, the narrow beamwidths required (0.3 $^{\circ}$ for 1000 foot altitude resolution at 20 miles) would result in a large antenna. As a result, no specific ASR-() elevation resolution requirement for general surveillance was defined. The use of multiple-

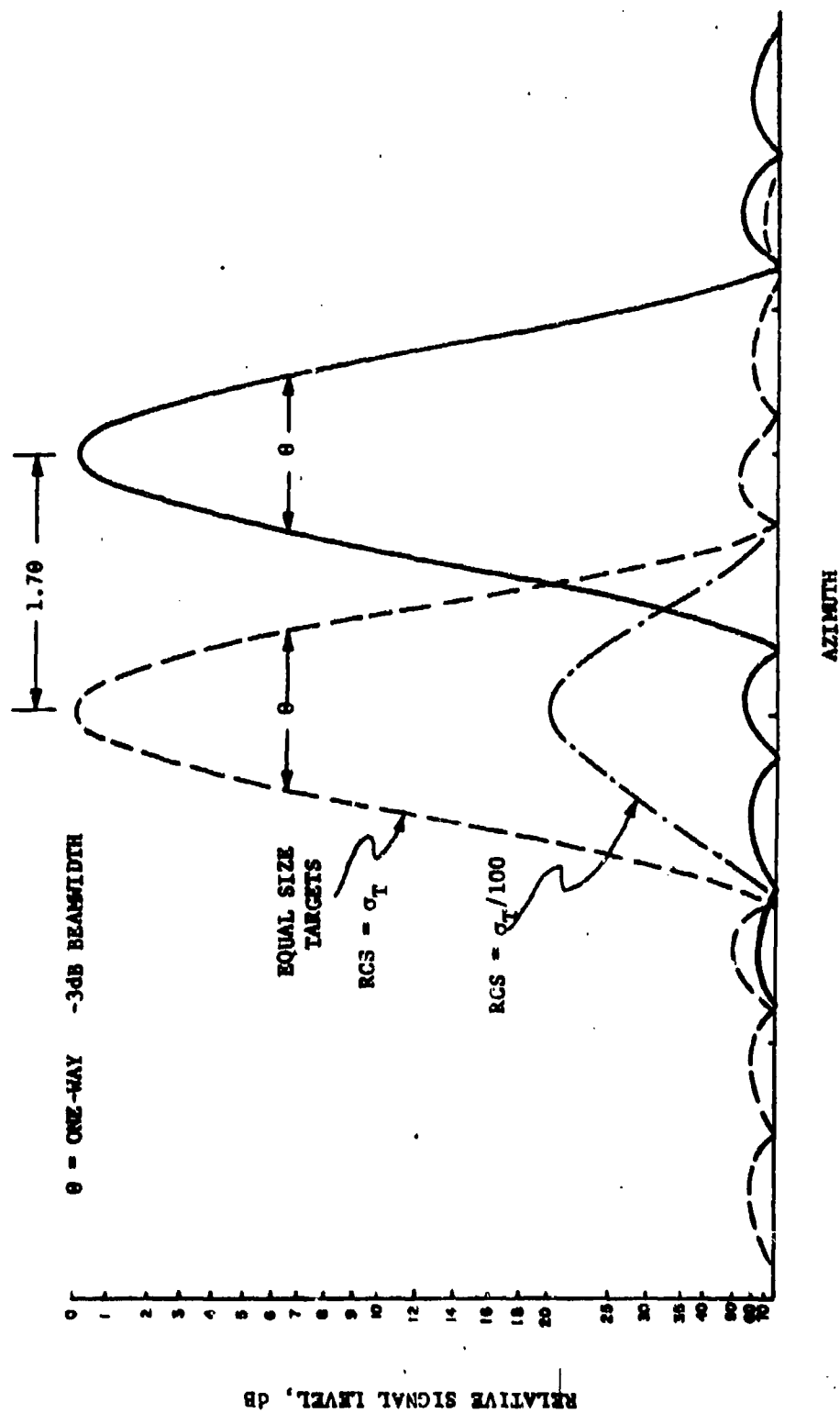


FIGURE 2-2 RELATIVE SIGNAL LEVELS FOR TWO AIRCRAFT SEPARATED BY 1.70

TABLE 2-1
IMPACT OF SEPARATION STANDARDS ON ASR-() BEAMWIDTH

SEPARATION STANDARD	DISTANCE	RANGE	EQUIVALENT ANGULAR SEPARATION	CORRESPONDING ASR-() BEAMWIDTH*
I PRESENT	3 nmi	to 40 nmi	4.3°	2.82°
	5	40-60	4.8°	
II PRESENTLY PROPOSED	1.5 nmi	to 15 nmi	5.7°	3.35°
	3	15-40	4.3°	
	5	40-60	4.8°	
III FUTURE	2 nmi	to 40 nmi	2.86°	1.69° 2.24°
	2 nmi	to 30 nmi	3.82°	

* PROVIDES CROSSOVER AT -20 dB POINT

beam elevation patterns for clutter rejection is discussed in Section 3.

2.3.2 Range Resolution

The ASR-3 through 7 radars utilize a 0.833 microsecond pulsewidth, providing a range resolution of about 410 ft. or one-sixteenth of a nautical mile. Resolution of this order was judged adequate for the ASR-() and is compatible with the current ARTS-III system. Use of a significantly longer pulsewidth was not considered advantageous because the savings in transmitter peak power is not offset by increased return from distributed clutter and, since the ASR-() azimuth resolution is coarser than present radars (2.25° vs. 1.5°), it is desirable to keep the range resolution as fine as possible to preserve interclutter visibility. Use of substantially shorter pulsewidths would require substantially greater peak transmitter power and require a much larger number of processing cells in the signal processor.

Pulse compression techniques reduce the peak power required to obtain a given range resolution. A long coded pulse is transmitted and, by matched filter processing, is compressed to provide the resolution of a much shorter pulse. However, a side lobe energy in the return pulse is spread out over twice the length of a compressed pulse. This effect can mask weak targets in the vicinity of much stronger targets. The effect is much like the antenna pattern shapes shown in Figure 2-2 although amplitude weighting can reduce time sidelobe levels at the expense of loss in peak target response. If pulse compression is used to reduce the peak power requirements of the ASR-(), the transmitted pulse must be short enough to meet the minimum range requirement of one nautical mile (12 microseconds) after allowing for T/R device recovery time, and the time sidelobes must be low enough to prevent masking of small aircraft (eg. $1M^2$) close to large aircraft or ground clutter returns (eg., 100-1000 M^2). The possible application of pulse compression techniques for the ASR-() is discussed in Section 3.

2.3.3 Range Rate Resolution

By means of doppler filtering, coherent radars can in theory provide single scan measurements of target range rate (i.e., the incoming or outgoing component of target velocity). However, the ASR-() instrumented range requirement leads to selection of a radar pulse

repetition rate which necessitates ambiguities in either range rate or in range. Furthermore, aircraft return modulation from jet engine compressors and propellers can lead to coherent modulations which can make it difficult to determine airframe range rates. For the short time-on-target of the ASR-(), it is unlikely that two aircraft in the same range and azimuth cell could be resolved in doppler. As a result, no specific doppler resolution requirement was defined for the ASR-(), other than that required to properly detect moving aircraft in clutter.

2.4 Accuracy and Data Rate

Accuracy is the precision to which the position of a target is measured on a single scan by the radar. Data Rate is the rate at which new position reports are provided by the radar and corresponds to the time required by the radar antenna to scan 360° in azimuth.

2.4.1 Angle Accuracy

With reasonable signal processing complexity, it is possible to reliably measure target angular position to an accuracy of one-tenth the radar beamwidth. Using the 2.25° beamwidth of Section 2.3.1, the resulting angular accuracy at range out to 40 nmi would be about 0.22° . This was judged to be acceptable for the ASR-() and compares favorably with Discrete Address Beacon System (DABS) specifications of $\pm 0.1^\circ$ azimuth accuracy.

2.4.2 Range Accuracy

DABS range accuracy is specified as ± 150 feet with a rms error of fifty feet. While it is possible to provide high range accuracy in the ASR-() through complex pulse-splitting techniques in the signal processor, this leads to expensive processors due to the need to process each portion of the radar pulse separately. For the ASR-(), a 2:1 pulse-split was chosen as a reasonable compromise; this leads to a 200 foot rms range accuracy (1/32 nautical mile). With a 200 foot range accuracy and 0.22° azimuth accuracy, target position error in range is less than the error in azimuth for ranges in excess of 8.6 miles.

2.4.3 Data Rate

The ASR-7 and ASR-8 operate at a rotation rate of 12.5 RPM, corresponding to a data rate of 4.8 seconds. The ASR-3 to 6 radars are designed for a nominal data rate of 4.0 seconds (15 RPM).

The current Discrete Address Beacon System (DABS) is designed to operate at a four second data rate. Thus, the ASR-() must fulfill its performance requirements at a four second data rate to permit use of a common DABS/ASR-() pedestal in locations where this is advantageous. If the radar is designed to meet its performance requirements at 15 RPM, it will still meet these requirements if used at lower RPM at non-DABS sites; the reverse is not generally true.

2.5 Interfaces with Other Systems

The major function of the ASR-() is to provide primary radar data to an automated air traffic control (ATC) system. The ASR-() will be designed to provide aircraft report data in digital form for use in the ARTS-II or ARTS-III systems, and it must also interface with a co-located beacon interrogator system, either DABS or ATCRBS.

Interfaces with these systems are described in detail in the sections that follow.

2.5.1 Output Data Interface

Figure 2.3 is a generalized diagram showing the type of processing performed in the ASR-(). In a modern radar such as the ASR-() the quadrature video signals are converted to digital form in the signal processor and all further processing is performed digitally.

The signal processor provides a number of doppler filters for each range-azimuth cell. These filters are used to separate ground clutter, rain, sea clutter, automobiles, bird flocks, etc. from the desired aircraft returns. The output of each filter is thresholded using adaptive thresholds generated within the signal processor and based on the level of ground clutter, rain return and noise in the vicinity of the range-azimuth cell. The output of the signal processor consists of primitive detection reports, each describing a threshold

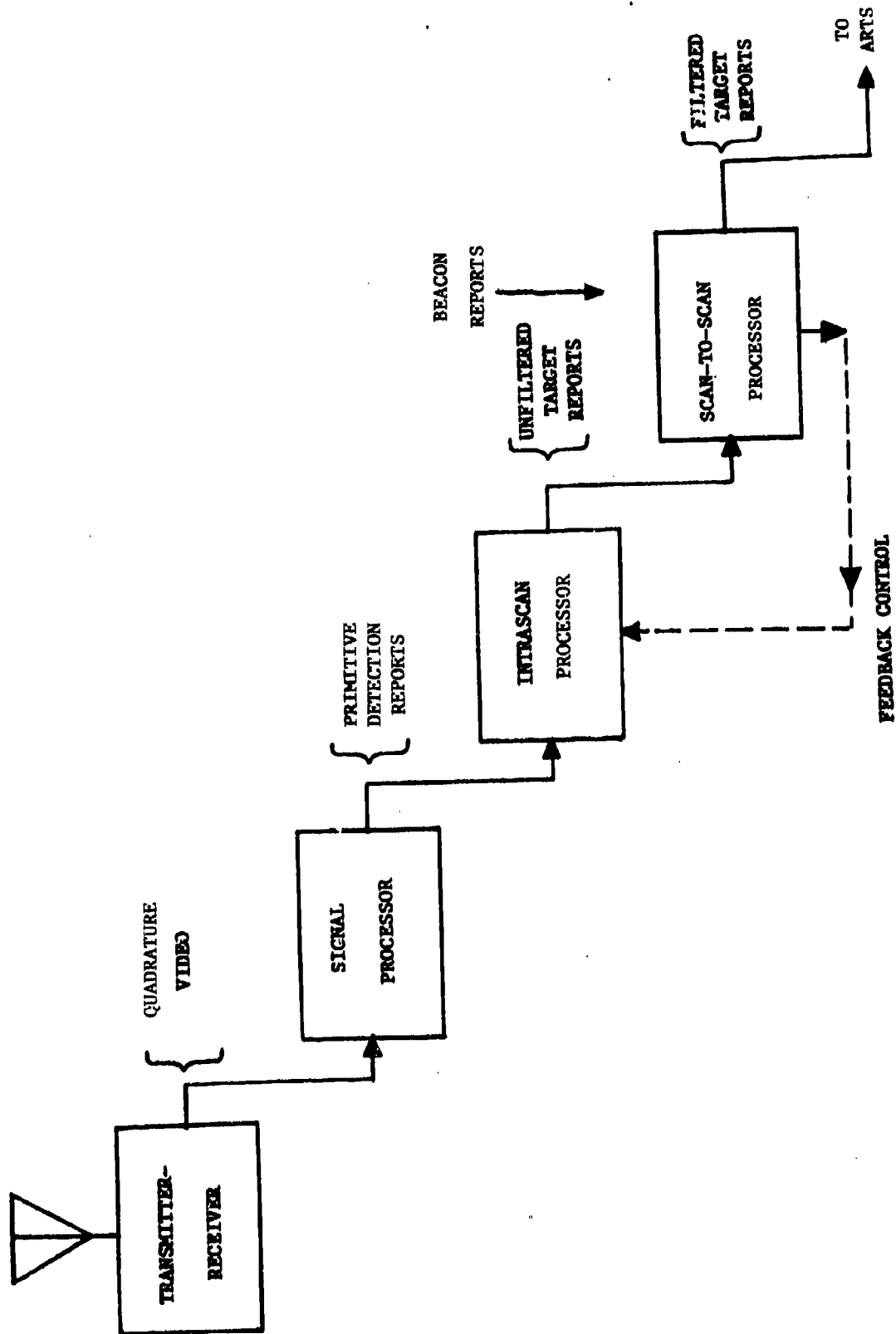


FIGURE 2-3 ASR-() SIMPLIFIED BLOCK DIAGRAM

crossing in one of the range-azimuth doppler cells.

The purpose of the intra-scan processor is to: 1) consolidate primitive detection reports from the same aircraft and through parameter estimation to provide a single report giving range, azimuth radial velocity and strength on each aircraft detected; and, 2) to provide a second threshold so as to eliminate many residual reports which occur due to bird flocks, simultaneous pulse interference and heavy clutter. The intra-scan processor sets this second threshold on a sector basis using data derived from the scan-to-scan processor. The output of the intra-scan processor consists of unfiltered target reports.

The final target filtering is performed in the scan-to-scan processor. Here the unfiltered reports are associated from scan to scan to see if they form a reasonable track corresponding to an aircraft. Slow tracks from bird flocks are eliminated. Beacon reports are correlated with radar reports to aid in the identification of the proper track with which to associate each target report. The resulting filtered target reports are passed on to the DABS or ARTS automated control systems.

As the signals pass through the various levels of filtering, the required data rate is gradually reduced as shown by the following table. Note that for either the unfiltered or filtered target reports the data rate is low enough to pass over a telephone line provided the peak bit rate is averaged with an input buffer. There is, however, a feedback from the scan-to-scan processor used to set the second thresholds in the intra-scan processor so that ideally these functions should be performed in the same processor or at least in processors in close proximity to each other.

Table 2-2 Approximate Data Rates Based on 100 Aircraft

	<u>Average # per second</u>	<u>Average Bit Rate</u>	<u>Peak Bit Rate</u>
Primitive Detection Reports	800	10K bits/sec	150K bits/sec
Unfiltered Target Reports	140	1408	5200
Filtered Target Reports	100	1250	3750

This processor should also be programmed to provide continuous operational status information on key ASR-() subsystems. The program for this processor could be hard-wired after system development is completed.

Performance requirements for the ASR-() output are as follows:

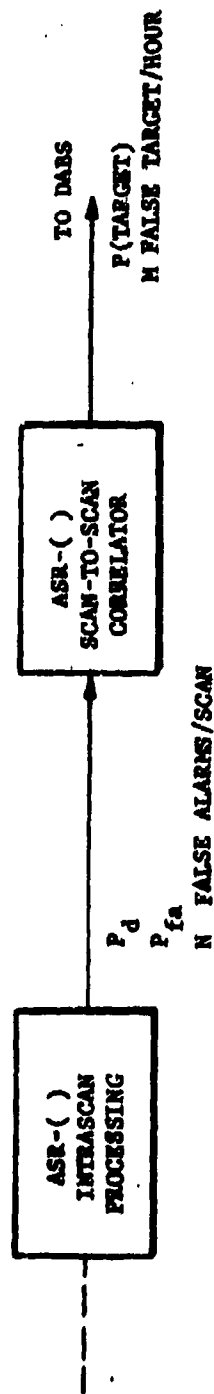
- a) Minimum size aircraft ($1M^2$) in the ASR-() coverage (40 nmi) shall be initially output in four or five scans.
- b) No more than one false target per hour shall be output.
- c) A probability of detection high enough to provide track lifetimes greater than 200 scans shall be assured

Rapid acquisition of aircraft in key areas (such as at the end of the runway for departures) can be performed by accepting lower validity codes in these specific areas. Figure 2-4 provides two examples of acquisition logic which meet the above requirements. Appendix B describes these logics in more detail and provides graphs of target validity states as a function of detection probability (P) at the output of the intrascan correlator. In addition, the system should maintain a track life in excess of 200 scans for aircraft with blip/scan ratios in excess of 0.75 within the required ASR-() coverage area.

2.5.2 Interface with the Automated Radar Terminal System

At DABS sites, the ASR-() would interface with ARTS-III via DABS. At non-DABS sites, the interface should be between the scan-to-scan correlator and the ARTS-II Input Output Processor (IOP) at the same level as the current Radar Data Acquisition System output. An alternative approach would be to use the Common Digitizer format and input data to ARTS-III as though the ASR-() were a remote Air Route Surveillance Radar, but this would complicate the radar-beacon correlation function.

Use of the ASR-() at non-ARTS sites is not envisioned since the primary objective of developing the ASR-() is to provide a high performance radar appropriate for use in major high-density terminals.



ACQUISITION LOGIC	A	B
ACQUISITION CRITERIA	2 HITS ON 3 SCANS	2 HITS ON 3 SCANS + 1 HIT ON 3 SUBSEQUENT SCANS
DROP TARGET CRITERIA	7 CONSECUTIVE MISSES	3 CONSECUTIVE MISSES
P(TARGET) FOR $P_d = .75$	≈ 1.0	.94
FALSE TARGET RATE	M = 1 PER HOUR	M = 1 PER HOUR
P_{fa}	4.4×10^{-6}	8.5×10^{-5}
FALSE ALARMS PER SCAN	N = 0.76	N = 14.7
ACQUISITION DELAY MEAN STANDARD DEVIATION	2.8 SCANS 1.2 SCANS	4.1 SCANS 1.6 SCANS

FIGURE 2-4 TWO EXAMPLES OF ACQUISITION LOGIC

2.5.3 Interface with ATCRBS Antenna

The ASR-() antenna must be capable of supporting the Air Traffic Control Radar Beacon System antenna. If a common-feed ASR-()/DABS antenna is developed, it would also be useable with the ATCRBS/ARTS system.

2.6 WEATHER DATA REQUIREMENTS

2.6.1 Weather Outline Information

The ASR-() must provide weather outline information which is at least as good as that of the ASR-7 and ASR-8 radars. The reliability of this type of information is poor because rain intensity is not generally a good indication of weather which is hazardous to aircraft, and because the apparent rain intensity observed by the radar varies with:

- a) the height of the precipitation volume in relation to the antenna elevation pattern
- b) the range rate of the storm in MTI video
- c) the amount of land clutter in the vicinity of the storm in non-MTI video

As a result, current ASR radars provide only an indication that weather is present but no reliable indication that the detected weather may be hazardous to aircraft. Item a) above greatly reduces the reliability and utility of attempts to provide calibrated contours of rain intensity; it therefore seems useless to clutter the displays with numerous contours of rainfall rate.

2.6.2 Hazardous Weather Information

Weather conditions which are hazardous to aircraft are hail, turbulence, and up- or down-drafts. In the absence of detectable precipitation, extremely powerful radars can detect clear-air turbulence but this capability is clearly beyond expectations for an economical air traffic control radar.

Discussions with experienced air traffic controllers indicate that the need for detection of hazardous weather conditions in the terminal area is a real one, although FAA has no formal responsibility for guaranteeing safe aircraft passage through weather. The need for reliable hazardous weather data increases as radar range decreases, since aircraft density increases and the altitude available for aircraft recovery decreases as aircraft approach the airport. The Radar Study Group concluded that 25 miles was a reasonable goal (from an operational point of view) for providing hazardous weather information via radar. As a result, the ASR-() study considered the air traffic control and weather hazard conditions separately. The ASR-() design parameters were established

without regard for providing any weather data over and above the weather outline capability of present ASR-7 and 8 radars (Section 3).

2.7 Reliability, Maintainability, and Availability

These areas were not deemed to be within the scope of this study and hence were not covered per se. However, in selecting ASR- () parameters, the primary objective was to define a design which provided sufficient performance on a reliable basis for major high-density air terminals. It was the general concensus that the reliability maintainability and availability of the ASR-() should be at least as good as those of the ASR-7 and ASR-8.

2.8 Life Cycle Cost

The Radar Study Group selected annual cost as the meaningful measure of the cost of the ASR-().

3.0 SELECTING THE OPTIMUM DESIGN

The approach used in determining an optimum ASR-() radar configuration is described in this section. The radar meets all operational requirements described in the previous section. Signal processing and antenna techniques used to solve the clutter problems are discussed first, then transmitter power requirements for several candidate radars are calculated, and finally initial and annual costs are estimated.

3.1 Clutter Reducing Techniques

The most difficult task in designing an air surveillance radar is in coping with clutter return ^(6,7). Unwanted radar signals are reflected from objects such as: (1) fixed ground objects (buildings, trees, etc.), (2) precipitation, (3) bird flocks and (4) ground vehicles. In addition, anomalous propagation often causes bending of the radar waves so that they intercept the ground at long distances causing ground returns due to the second to last pulse transmitted (second-time-around effect). Whereas there are a multitude of design features one could incorporate in a radar to reduce or eliminate each type of clutter separately, it is important that the overall radar design incorporate a set of features which are not mutually exclusive. A number of anti-clutter techniques will be briefly described, and their degree of usefulness and incompatibilities with other clutter reducing features indicated.

Before doing this, however, brief descriptions of the magnitude of the problem for ground clutter and rain are given. There isn't any general agreement on the magnitude of the ground clutter problem. Figure D-1 (Appendix D) shows most of the data presented by Nathanson ⁽⁸⁾. Where the radar is high enough so that not much shadowing exists, the mean value of clutter, σ_0 , follows a log-normal distribution, but the levels reported for presumably similar conditions vary widely (see Figure D-1). Looking at the data one can make no generalizations concerning dependency on wavelength or pulse length. It is difficult to pick a design value for σ_0 , but it is obvious that one wants the best clutter rejection possible. If we consider $\sigma_0 = -15$ dB for example, a typical ASR with 1.5 deg. azimuth beamwidth and a 1 μ sec pulse will produce a 3000 m^2 clutter backscatter signal from a range gate at 20 nmi. To automatically detect an aircraft with a 1 m^2 cross section requires a 15 dB signal-to-interference ratio, so the total improvement factor must be 50 dB. This would give aircraft detection ranging from 75 to 98%, depending on which curve in Figure D-1 applies.

The frequency of occurrence of various instantaneous rain rates is depicted in Figure D-3, Appendix D. A heavy rain of 16 mm/hr, which occurs about 0.3% of the time in Miami (27 hours/year) will cause a radar return of 16 m^2 for a 12,000 ft. high rainfall at 20 nmi in a typical S-band ASR. Again, since a +15 dB signal-to-interference ratio is required for automatic detection, an improvement factor of about 27 dB is required to detect the 1 m^2 aircraft. About 15 dB can be achieved using circular polarization. The rest must be achieved by some other technique.

3.1.1 Uptilting the Antenna

A common practice today to obtain better detection against ground clutter is to tilt the antenna up so that the peak of the beam is 3 to 4 degrees above the horizon (Figure 3-1). This reduces the ground clutter 15 to 20 dB so that much less improvement factor is required to see aircraft near the peak of the beam. Thus, aircraft coming in for a landing on a 3-degree glide slope are usually quite visible. Lower aircraft in the shaded region are out of the peak of the beam and are hard to detect over clutter. Thought will convince one that uptilt will not help in detecting a small aircraft only 1,000 ft. high over strong clutter at 15 nmi. A better improvement factor must be found. Aircraft are also lost over clutter in the upper shaded part of the antenna pattern (Figure 3-1) because the gain is greatly reduced due to the cosecant-squared pattern shaping.

3.1.2 Zoom Antenna, Constant Gain with Elevation, Integrated Beacon Feed

Since it has been concluded that an uptilted cosecant-squared elevation pattern isn't really helpful in detecting many targets against ground clutter, the question arises as to what beam shape should be used. Before answering that question, it should also be pointed out that the cosecant-squared beam is very poor when trying to see aircraft in the vicinity of moving clutter (rain or bird flocks). As an example, consider rain or birds at a range of 15 nmi and a height of 6,000 ft. They will be at the peak of the beam at a 3- to 4-degree elevation angle. An aircraft also at 15 nmi, but at 25,000 ft. will be at a 15-degree elevation angle. The aircraft will be at a 20 dB disadvantage with respect to the rain or birds. Use of the STC aggravates the problem caused by the cosecant-squared antenna since the R^{-4} function truncates the higher elevation portion of the pattern (Figure 3-1) out to the range extent of the STC.

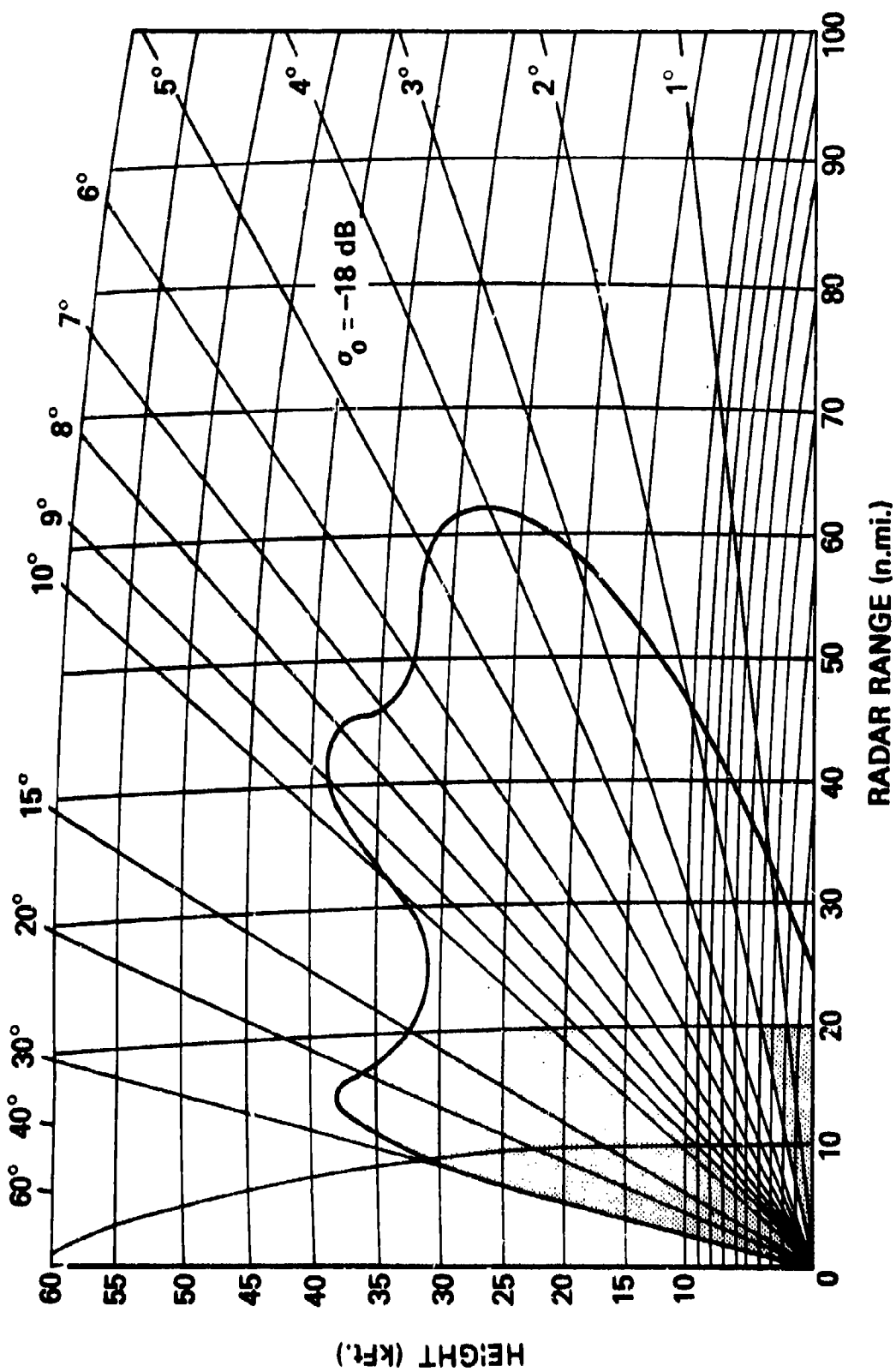


Figure 3-1

COVERAGE OF ASR-7 RADAR AGAINST A 2-M² TARGET

Recently designed ATC radars (domestic and foreign) use antennas that transmit on a single pattern which is either modified cosecant-squared or "thumb" type, and have the option of receiving on the same pattern or a scanned-up version (or both). Although this combination represents an improvement over some of the older designs, it is not totally satisfactory because of the residual problems caused by STC, angel clutter and precipitation.

The next step in the evolution of the elevation pattern will, by necessity, be a somewhat larger one than those which have led to today's configurations. We have named the desired feature "zoom" because of its similarity to the optical analog; it consists of optimizing the two-way pattern as a function of target slant range, primarily by a change of beamwidth. Since the transmit pattern must be constant, this can only be done by varying the receive pattern as a function of time during a range sweep. Figure 3-2 depicts the "ideal two-way pattern as a function of range within an altitude-limited coverage volume. With this two-way pattern, no aircraft is at a disadvantage with respect to rain or birds because of its elevation position within the beam up to maximum altitude for which the system was designed.

A number of possibilities exist but a particular configuration is being pursued at Lincoln Laboratory since it seems to offer the best combination of hardware simplicity and performance stability. The basic scheme consists of mating a stacked elevation beam antenna with a controllable beam distribution system (Figure 3-3). The multiple beam antenna is realized by an offset paraboloidal reflector with stacked feedhorns. The beam distribution system consists of a fixed transmit power divider duplexed with a variable receiver power divider (combiner). The implementation of the latter depends on the degree of flexibility desired. The example shown on Figure 3-4 provides maximum capability in the sense that an almost continuous range of adjustments is available between two extremes: 1) only one beam, or 2) all beams on. The fewer the number of steps, the simpler the device becomes. One such possibility is shown on Figure 3-5 corresponding to only one transition.

The multiple beam paraboloidal antenna offers a number of attractive features. Firstly, the high rate of cut-off at the horizon is maintained for all beam shapes, and this is accomplished typically with about half the vertical aperture needed for cosecant-squared or "thumb" ⁽⁹⁾ designs with spoiled reflectors. By keeping the number and complexity of individual radiating sources relatively low, multiple polarization

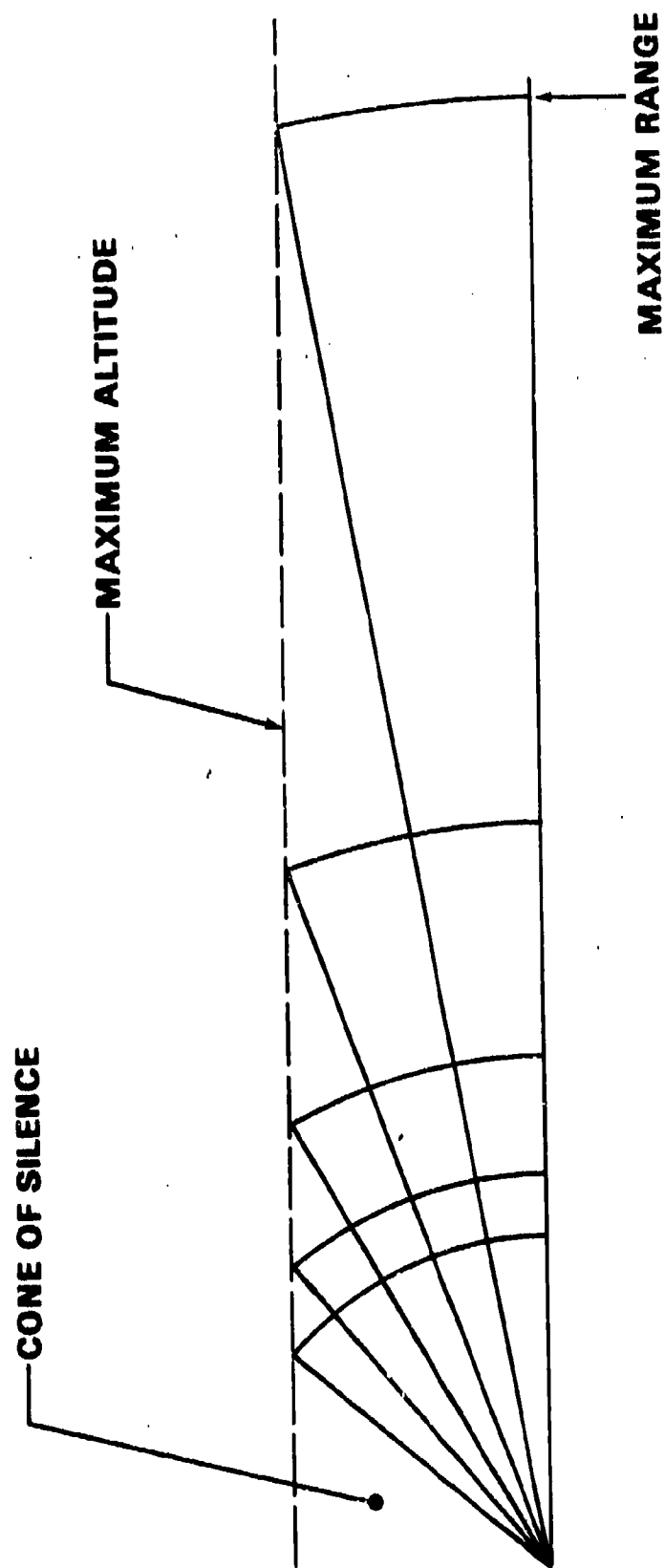


Figure 3-2. Two-Way Patterns for Optimum Coverage

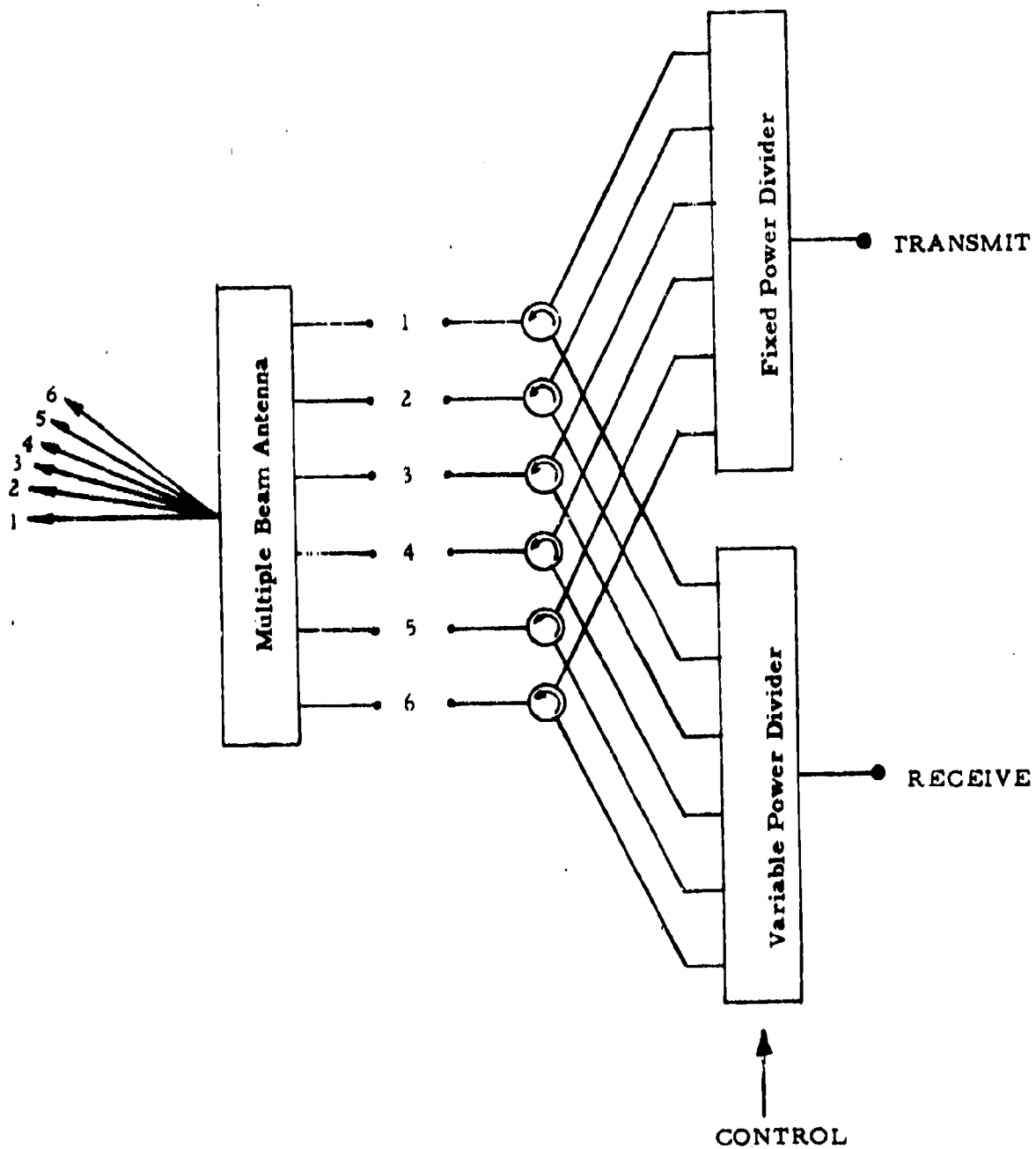


Figure 3-3 "Zoom" Antenna System

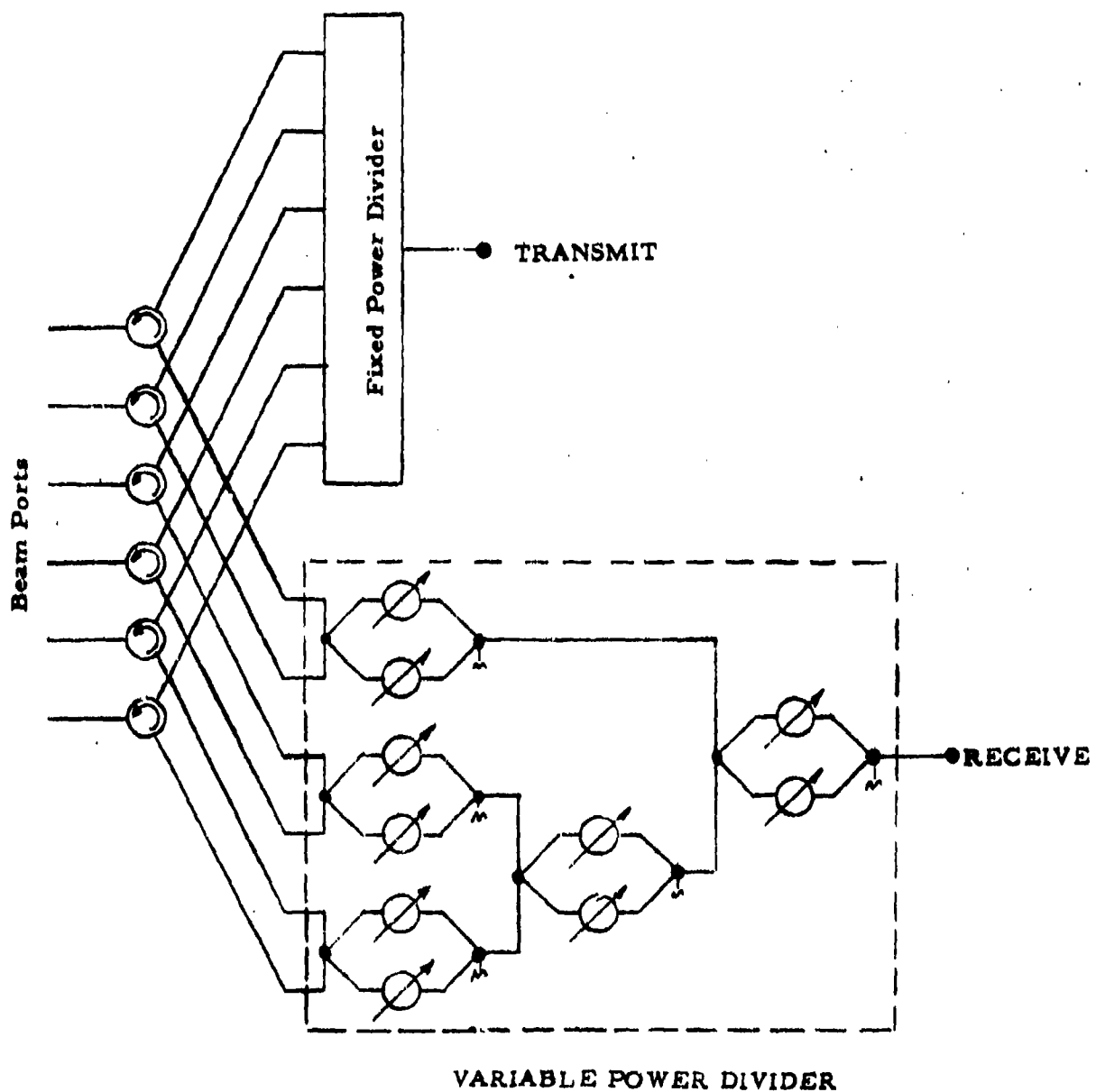


Figure 3-4. "Zoom" Antenna Variable Power Divider Implementation

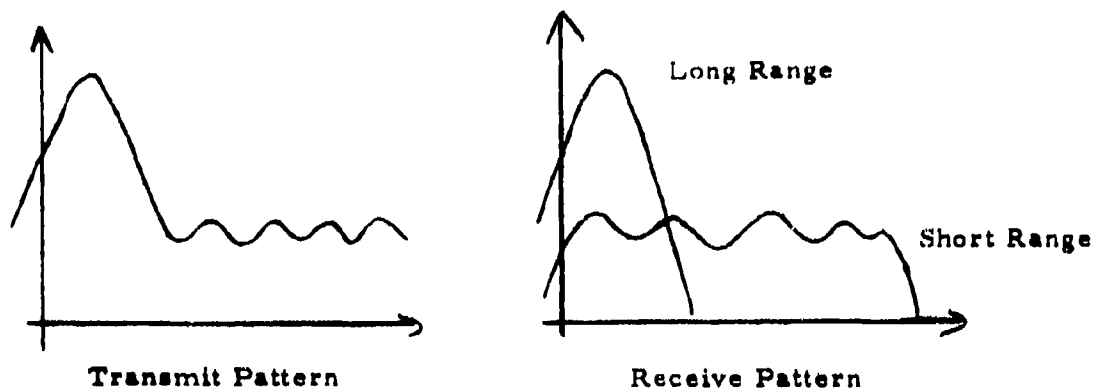
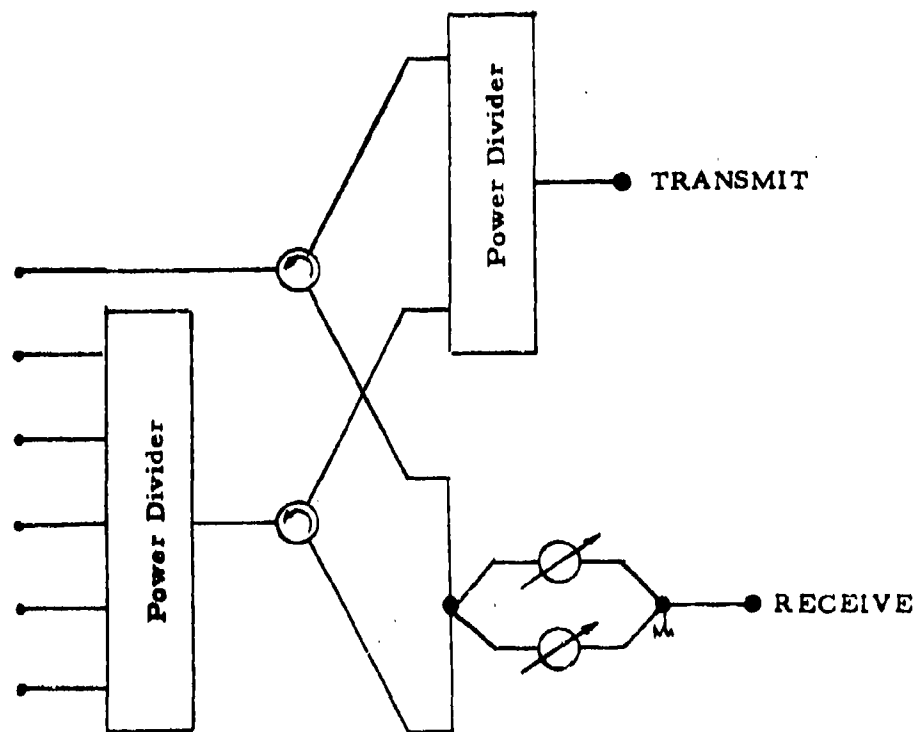


Figure 3-5. Limited "Zoom" Feed Network

capability is still practical and, of course, beam control is simplified.

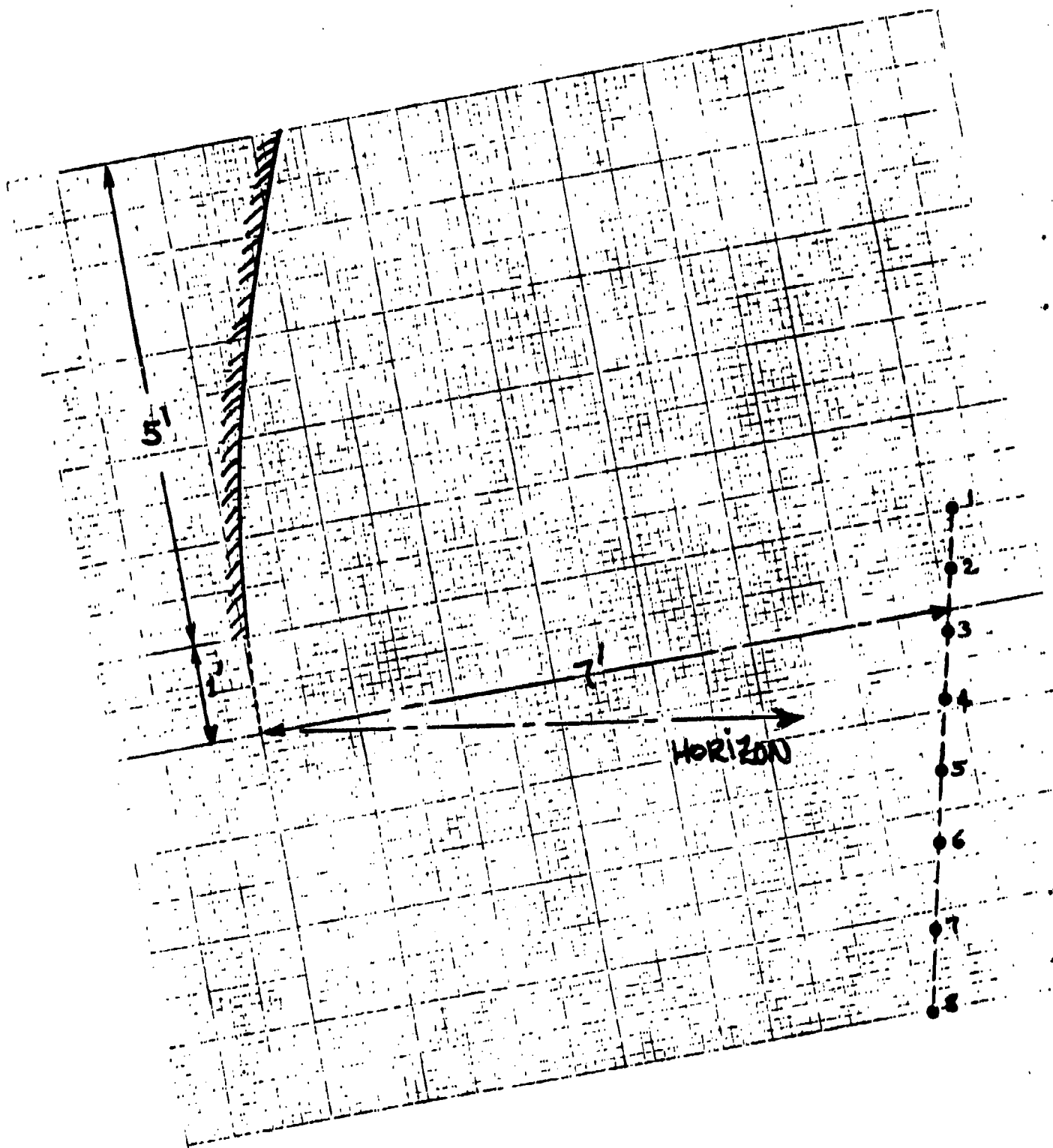
Typical results for the kind of pattern control which can be obtained from the full capability "zoom" are shown on Figure 3-6. The "thumb" transmit pattern was selected as a compromise between gain reduction and pattern variation over the coverage sector. The receive patterns were synthesized to counter the transmit pattern by an upward slope, resulting in nearly flat two-way patterns. Low side lobe azimuth patterns are maintained at all elevation angles.

3.1.3 Pencil Beams

Use of pencil beams is desirable from three points of view: (1) with narrow multiple pencil beams one could do height finding, (2) narrow beams would contain less rain clutter, and (3) all except the lower beam would contain much less ground clutter. However, (1) the FAA's ATC system, based mainly on beacon reports (altitude and identity), does not require aircraft height finding, although if the weather height measurement function were to be performed by the ASR it would require height finding, (2) To keep antenna size reasonable, the height finding would have to be done at S-band where rain is still a big problem. Rain filtering or thresholding would be required on all the beams, or else the transmitter and receiver would have to be time shared between beams. The first choice involves more complicated equipment, and the latter would reduce the number of pulses in the lowest beam where, as we shall see, more pulses are needed for adequate detection performance against ground clutter.

A single pencil beam would not contain significantly less rain clutter than a fan beam. At longer ranges (say 30 nmi) where the signal to rain clutter problem is worse, the vertical rain extent is usually limited by the elevation extent of the rain itself rather than the beamwidth. Only a 3 to 6 dB advantage could be expected.

Finally, if adequate performance against ground clutter can be obtained in the lowest beam, there is no reason why the same performance can't be achieved using a fan beam with much less equipment cost.



(a) Geometry

Figure 3-6 Example of Zoom Antenna Performance

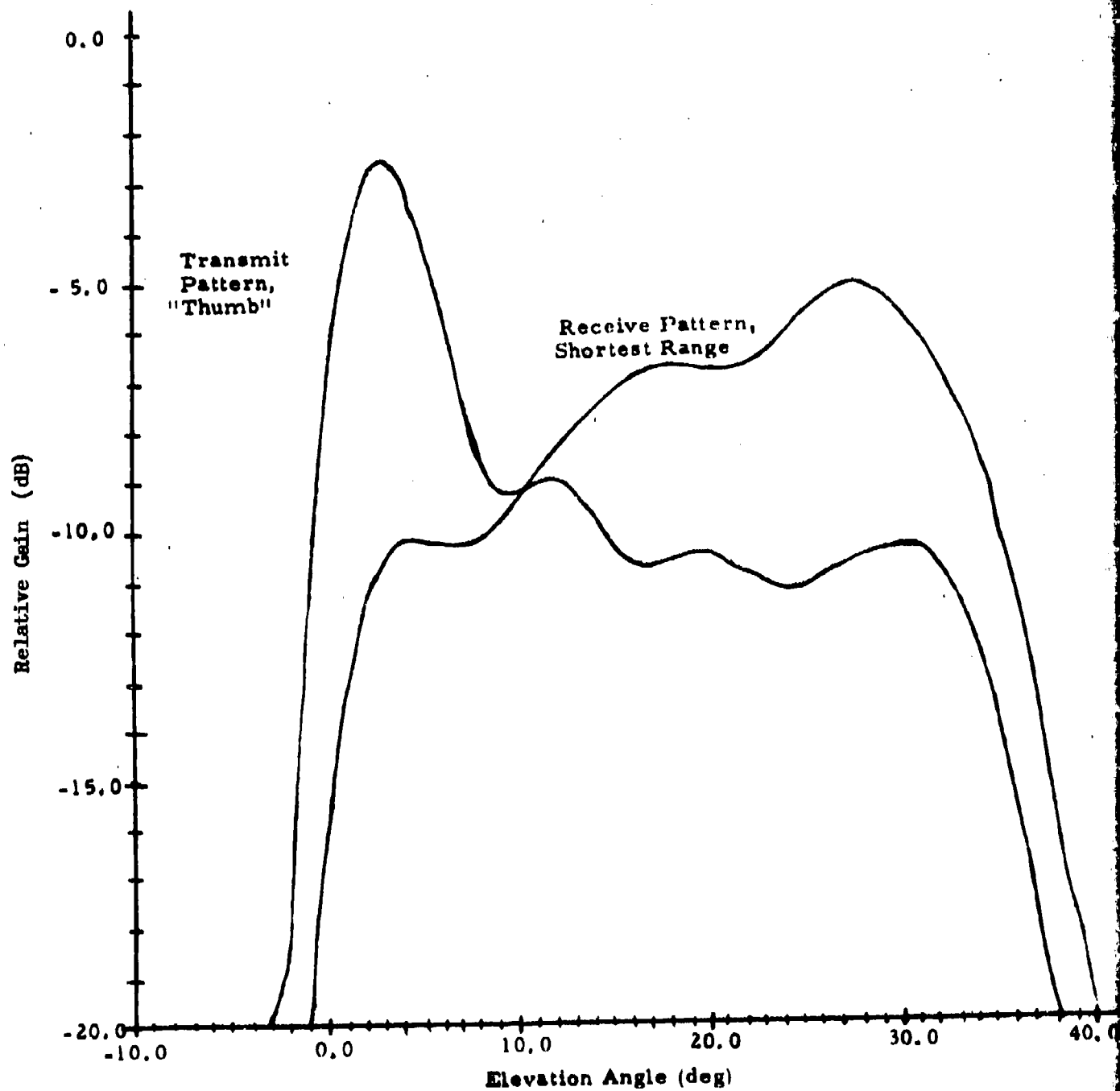


Figure 3-6(b), Example of "Zoom" Antenna Performance

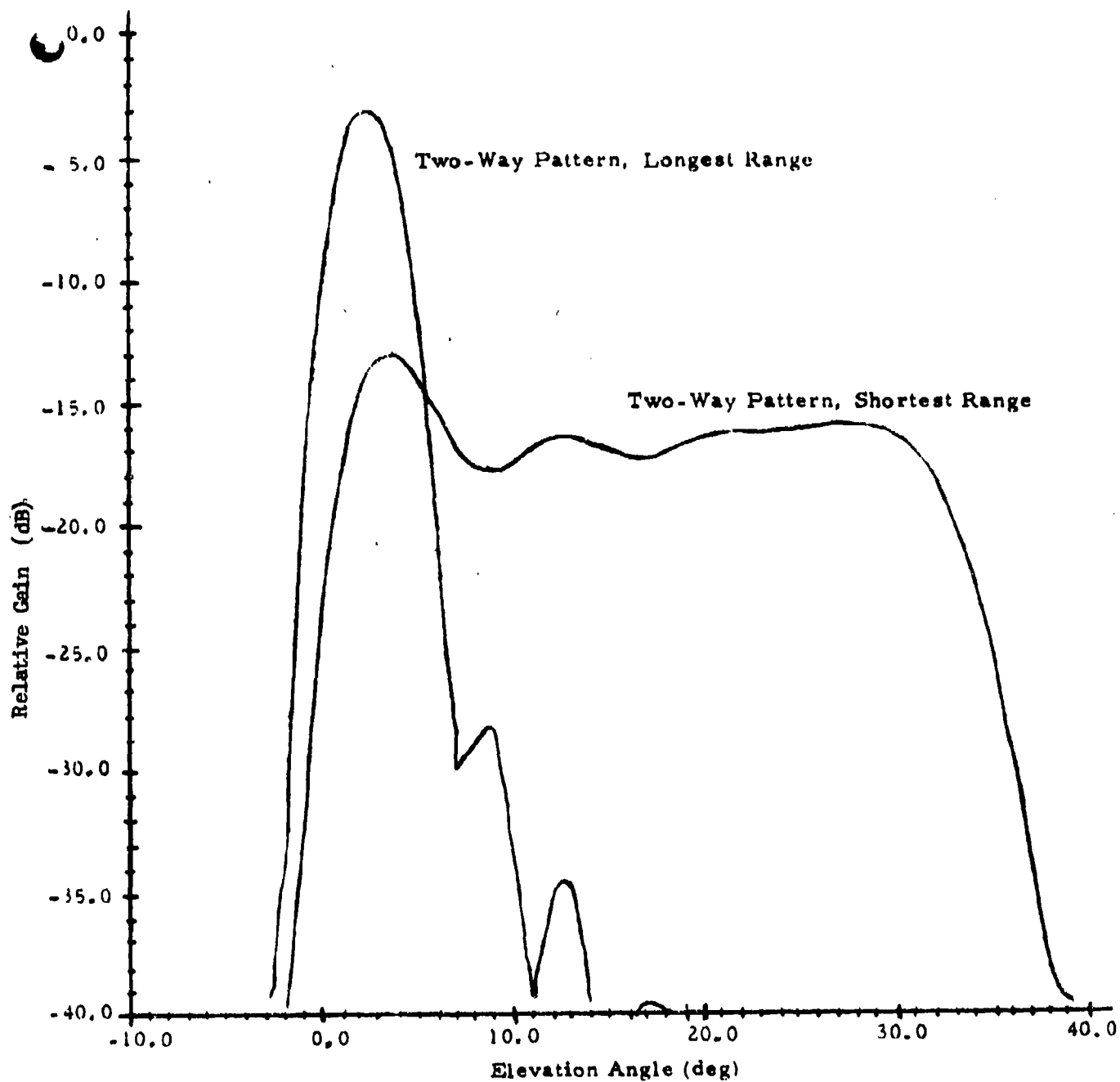


Figure 3-6(c), Example of Zoom[®] Antenna Performance

3.1.4 IF Limiter Followed by a Three-Pulse Cancellor

This is the classic MTI circuit used to reduce clutter. It is known ⁽⁹⁾ that the IF limiter spreads the clutter spectrum so that with 20 pulses per 3 dB azimuth beamwidth, the improvement factor is only about 25 dB as opposed to 45 dB without limiting.

Limiting is employed so that the clutter residue out of the three-pulse canceller will be approximately equal to the noise as viewed on the PPI. This requires that the limit level be set about 25 dB above noise, equal to the improvement factor under severe limiting.

3.1.5 Linear IF, Three-Pulse Cancellor and Mean-Level Threshold

Since limiting degrades performance, why not use a linear IF and some other form of threshold, say a mean-level threshold? The mean-level threshold samples the residue output for many cells on either side of the one being thresholded, finds a mean and sets the threshold proportional to it.

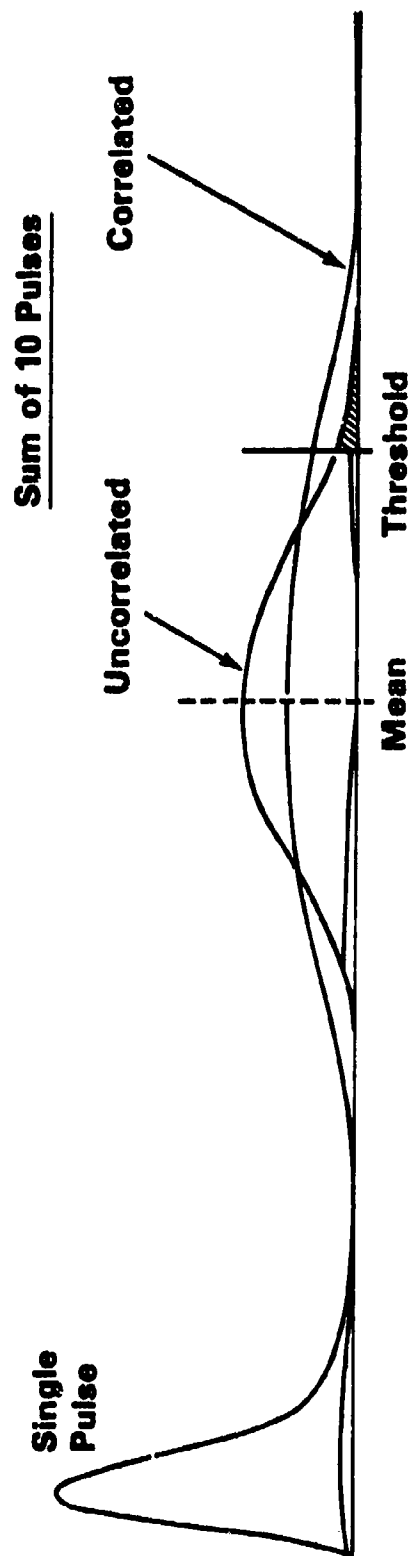
This scheme works except that the resulting improvement curve (sine-squared) is of poor shape, having a wide notch at the blind speeds and zero velocity. In addition, even at optimum velocity, only three pulses are coherently integrated so that the detection performance is poor in noise.

Adding feedback to the canceller circuit to sharpen its response is a possibility, but that unfortunately degrades the improvement factor by letting more clutter through.

3.1.6 Non-Coherent Integration or Sliding Window Detector

One might consider adding either a non-coherent integrator (enhancer) or a sliding window detector (nearly equivalent to a non-coherent integrator) to the last arrangement to recover detection performance in noise. This would be a poor choice as it has recently been discovered ⁽¹⁰⁾ that this procedure is the cause of all the false alarm difficulties experienced on rain clutter with the Common Digitizer (sliding-window detector).

It may be shown that if the detected clutter residue (rain return) is partially correlated from azimuth to azimuth that the statistical spread of the non-coherently added returns is much greater than from receiver noise which is uncorrelated. This is shown diagrammatically in Figure 3-7. If a threshold is established as some multiple of the



NONCOHERENT INTEGRATION (Probability Distributions)

Figure 3-7

mean receiver noise (see Figure 3-7), the false alarm rate will be equal to the area under the curve above the threshold. When rain occurs, the curve changes to the one marked "correlated" without a change in the mean so that the area above the threshold and the false alarm rate go up by orders of magnitude.

The correlation of the clutter can be measured and the threshold raised accordingly, but it was shown⁽⁸⁾ that if this is done, most of the signal-to-noise improvement due to the non-coherent integration is forfeited.

3.1.7 Coherent Integration

If it is inappropriate to use limiting, a simple three-pulse canceller, non-coherent integration or sliding window detection, what circuits should the processor contain? It is known that best detection performance against noise or clutter may be obtained by coherent integration rather than non-coherent integration over as many pulses as practical. This avoids so called non-coherent integration loss, and, using linear circuits, one can also avoid the spectral spreading associated with limiters.

Several questions arise: (1) what weights should be used for the coherent integration? (2) Can the large clutter signals be handled or do they exceed the dynamic range of available circuits? (3) Is coherent integration too complicated and expensive from a hardware point of view? These questions are now addressed.

Coherent integration or filtering is a process whereby samples of the signal (consisting of clutter plus target plus noise) are each multiplied by some constant (not the same for each sample) and added together. The result is detected and thresholded to determine the presence or absence of a target. The problem of optimizing the weights to maximize the target-to-interference ratio has been solved theoretically⁽⁷⁾. Some results are presented.

The proper set of weights is a function of the size and autocorrelation properties of the clutter and noise signals. A different set of weights must be applied for each target velocity. Figure 3-8 shows improvement factors achievable using optimum weights when detecting aircraft with various radial velocities. The improvement factor is the ratio of target-to-interference ratio at the processor output compared to the single pulse target-to-interference ratio at the processor input. For our assumed ground

clutter model, an improvement factor of 50 dB is required at the processor input. Eight signal samples and a clutter-to-noise ratio of 40 dB have been assumed for them. The ground clutter correlation properties are described in terms of the number of pulses in a one-way, 3 dB antenna beamwidth. The antenna scanning motion is assumed to cause the decorrelation of the clutter signals. For these optimum processor curves, the target is assumed constant in amplitude. This assumption is made because there is not a priori knowledge of its position in the antenna beam (see Appendix C). The abscissa for these curves is normalized to the first blind speed, the prf converted to a velocity using the usual Doppler formula for radar ($f = 2v/\lambda$).

Figure 3-9 shows what happens when one varies the number of pulses coherently added in the optimum processor. Notice that the central portion of the curve increases in direct proportion to the number of pulses processed. In this central region, all of the ground clutter has been rejected so the target competes only with noise. The improvement factor in this central region is equal to the clutter-to-noise ratio times the number of pulses processed. Notice also that increasing the number of pulses processed above about eight, causes very little narrowing of the blind speed regions. Since the processing hardware complexity increases rapidly as the number of pulses increase, it is best to limit the number processed to eight.

Hardware implementation of the optimum processor just described is not trivial. First, it requires many multiplications. For eight signal samples, one would probably implement 8 velocity filters which would overlap well enough to avoid serious loss in the velocity regions where two filters overlap. Eight samples times 8 filters requires 64 complex multiplications be performed for each range-azimuth cell processed. A typical ASR requires the processing of 960 cells during 10 msec, the time it takes to collect the pulses. Thus, implementation of the optimum processor will require about 6.2 million complex multiplications per second or about 25 million simple multiplications.

Another difficulty with the optimum processor is that the set of weights to be used depend on the clutter-to-noise ratio which varies greatly over the area of coverage. A simpler processor seems in order.

The concept of an optimum processor, however, should not be ignored. The curves in Figures 3-8 and 3-9 can be used as a goal against which to judge the performance of any sub optimum processor. There is, in addition, a second way of defining an optimum processor which gives some insight into the process for choosing sub optimum processors. It is well known that when it is desired to optimize the detection of a known target signal in white noise, one uses a so called matched filter. Each sample of target plus noise is multiplied by the complex conjugate of the known target signal and the result added together. This process maximizes the target signal with respect to the white noise. If the noise is colored, it seems quite obvious to pass the signal through a pre-whitening filter which whitens the interference signal and then to pass the signal through a filter which is matched to the signal as modified by the pre-whitening filter (See Figure 3-10a). The same overall filter can be broken into parts, one dealing solely with the clutter, and one dealing solely with the signal (see Figure 3-10b). The clutter filter should have a response curve which is the reciprocal of the square of the clutter spectrum.

A search of various easily implemented filters shows that a simple two or three pulse MTI canceller, approximately matches the filter shape required for the clutter filter just described if the clutter spectrum is generated by a typical rotating ASR antenna.

Using the clutter filter described above, the proper target filter is a matched filter for a target in white noise. To handle targets at all velocities this becomes a filter bank or discrete Fourier transform. The most efficient discrete Fourier Transform is the so called Fast Fourier Transform (11) (FFT). An eight point FFT requires only 4 simple multiplications by $1/\sqrt{2}$. All the rest are simple additions and subtractions. Notice that the MTI cancellers require only additions and subtractions to implement. Also, one could implement a set of generalized pass band filters. These filters are much simpler to implement than the optimum filters because they are preceded by the MTI canceller.

The first MTD-I, a hard-wired processor built in 1973, used a three-pulse MTI canceller followed by an 8 point FFT. This choice was dictated by the desire to minimize hardware. With the rapid drop in cost of digital logic and memory, new implementations are now cost effective. The second generation Moving Target Detector (MTD-II) now being developed at Lincoln Laboratory will use two pulse MTI cancellers followed by simple generalized transversal filters.

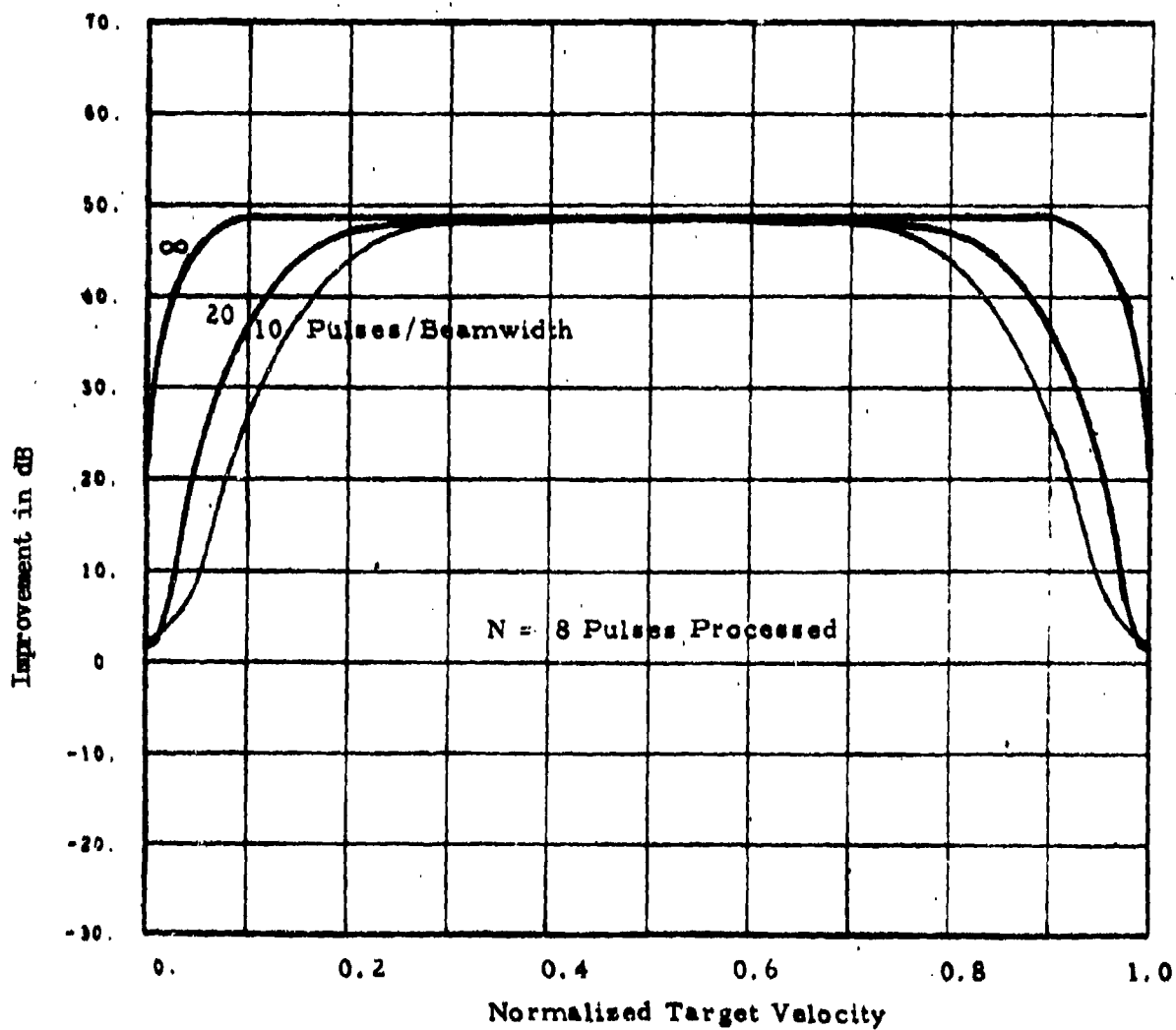


Fig. 3-8 IMPROVEMENT FACTORS FOR OPTIMUM PROCESSORS USED WITH ANTENNAS SCANNING AT VARIOUS RATES. THE ASSUMED CLUTTER-TO-NOISE RATIO IS 40 dB. THE TARGET VELOCITY IS NORMALIZED TO THE FIRST BLIND SPEED ($\lambda \times \text{prf}/2$).

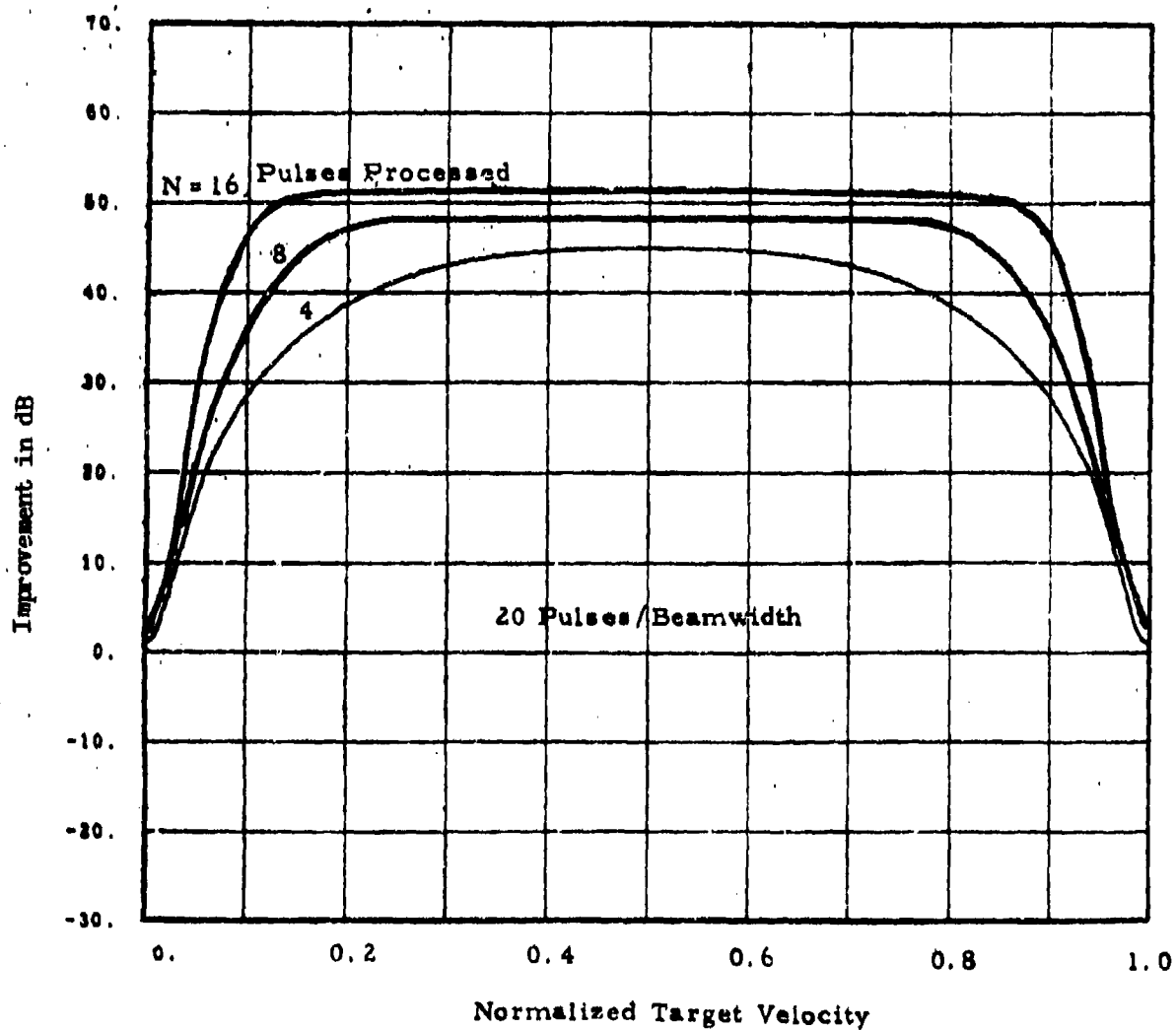


Figure 3-9 IMPROVEMENT FACTOR FOR OPTIMUM PROCESSORS USED WITH A SCANNING ANTENNA. VARIOUS NUMBERS OF PULSES ARE PROCESSED. THE ASSUMED CLUTTER-TO-NOISE RATIO IS 40 dB. THE TARGET VELOCITY IS NORMALIZED TO THE FIRST BLIND SPEED ($\lambda \times \text{prf}/2$).

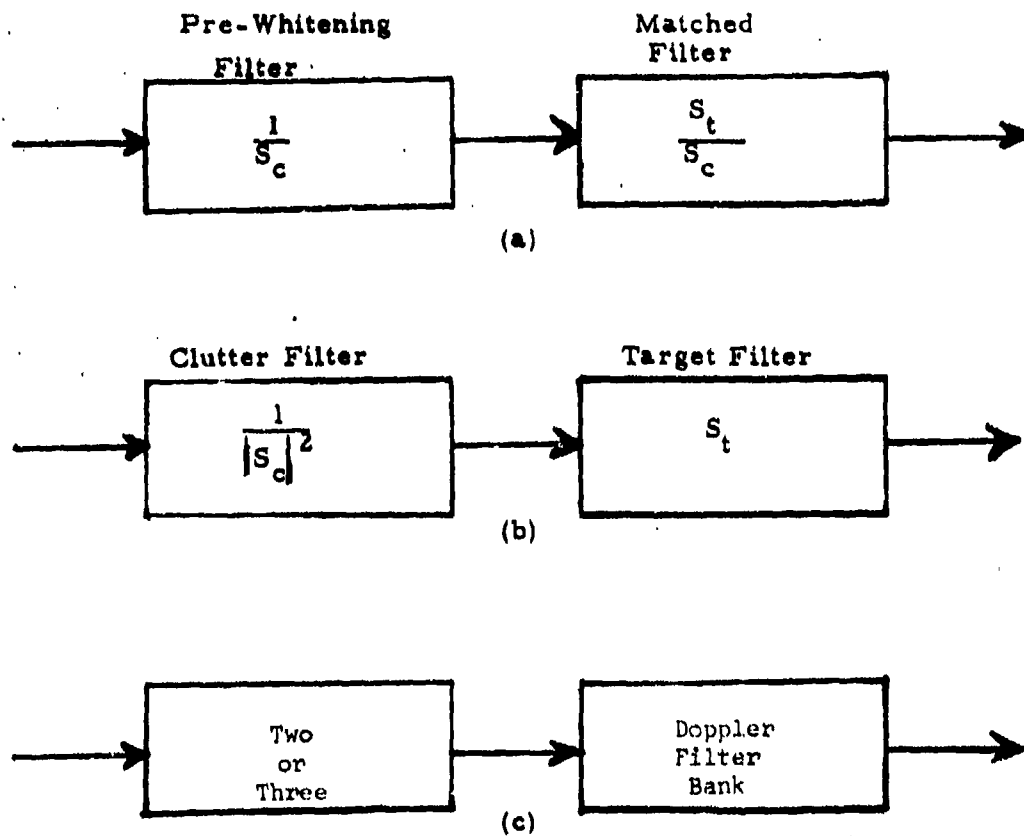


Figure 3-10 Conceptual Development of Near-Optimum Filter. S_c is the Clutter Spectrum. S_t is the Target Spectrum.

It should be noted that because the MTI canceller has a deep null at zero radial velocity, it is necessary to implement a separate zero velocity filter if it is desired to observe near-zero velocity targets or those at blind speeds.

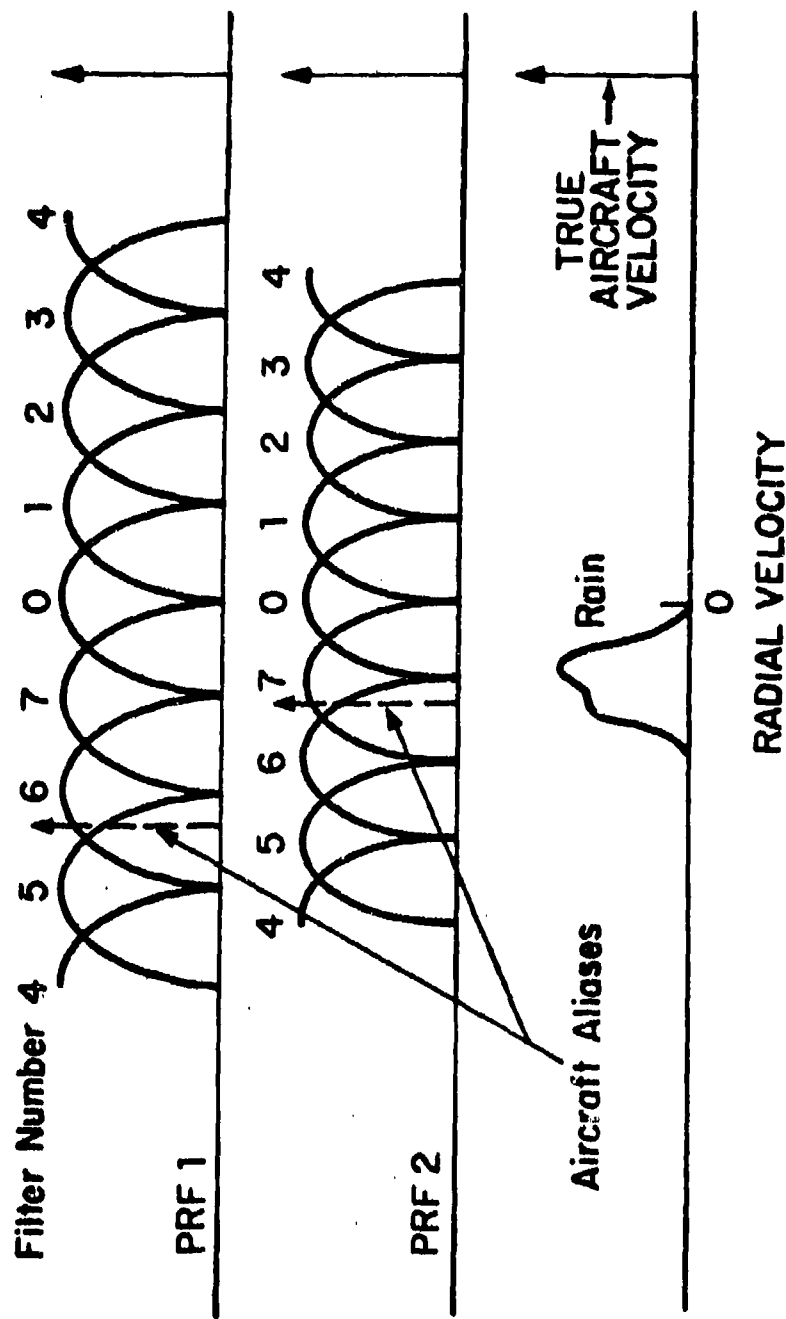
It should be pointed out that because the MTI canceller is a near optimum clutter rejection filter for the present ASR's with about 23 pulses per beamwidth, other clutter rejection filters will be better for other scanning arrangements. For instance, for an electronically step-scanned antenna, the optimum filter is an FFT filter because the spectrum of clutter returns is extremely narrow (1 Hz wide).

3.1.8 Thresholding and Clutter Management

Any radar which is to feed an automated system must include target detection thresholds. The threshold should also, as nearly as possible, produce a constant false alarm rate (CFAR) so that optimum detection performance will be achieved without at any time excessively loading the processor to follow.

The type of threshold to use and its adjustment for CFAR vary with the nature of the clutter. In what follows thresholds are discussed by clutter type.

(a) Rain Clutter: Because of the natural structure of rain storms, precipitation clutter generally varies slowly over distances of about a mile in a typical rain storm. The rain spectrum (Appendix D) depends on the wind field in the vicinity of the storm. Wind shear (variation with altitude) generally causes a spread of velocities of 10 to 30 knots, thus rain signals will usually come through two or three of the filters in an eight-point FFT. This is depicted in Figure 3-11. Two steps need to be taken to properly threshold and manage rain clutter. (1) A mean-level threshold should be used to generate the threshold. All range cells for about one-half mile on either side of the one of interest are sampled at the same velocity (same filter output). A mean-level of clutter is calculated and that mean used to establish a threshold. This threshold will be calculated from statistically independent samples so will not suffer the disadvantages imparted by non-coherent integration described previously. (2) The prf should be changed periodically to move the aliased



DETECTION IN RAIN USING TWO PRF'S

Figure 3-11. Response of a Filter Bank to Rain and an Aircraft Whose Return is Aliased in Velocity

targets to different filters so that blind speeds are largely eliminated. This is shown in Figure 3-11 where a higher speed target is aliased into the rain on prf-2, but into a filter free of rain on prf-1.

(b) Ground Clutter Map: By its nature, ground clutter varies widely from spot to spot so that mean-level thresholding using samples in range is impractical. To get a good estimate of the ground clutter, an average must be taken over a relatively long period of time. This leads naturally to the ground clutter map as an instrument for ground clutter management. A ground clutter map is a storage device containing the mean-level of the ground clutter (zero velocity) return in each range-azimuth resolution cell of the radar. The mean level is obtained by use of a recursive filter on a scan-to-scan basis. A fraction of the new value (say 1/8) each scan is added to one minus that fraction (7/8) of the value stored in the map. In this way, the map is automatically built-up and changes automatically when the zero velocity clutter changes, as when rain comes into the radar's coverage.

The clutter map can be used to set thresholds proportional to the mean clutter level. Also, knowing the spectral spread of the ground clutter and the shape of the other filters, one can calculate the level of ground clutter leakage into these filters and an appropriate ground clutter threshold calculated for each.

The ground clutter map supplies the following functions:

(1) By thresholding just above the ground clutter or noise level in each range-azimuth cell the radar's interclutter and superclutter visibility is improved. Tangential targets with near-zero radial velocity and blind speed targets are seen if their cross section is larger than the return from the cell over which they are flying.

(2) Since some ground clutter leaks into the other filters, the ground clutter map levels can be used to establish a threshold against this leakage for the other filters.

(3) A few cells in the area of coverage will have very large clutter returns (10^4 to 10^6 m²) which may overload the signal processor, see Appendix D. The clutter map senses these and provides circuits arranged to cope with them. These cells can be blanked, or attenuation added in the receiver ahead of the analog-to-digital converters, or the map may

be used to provide scaling values for the analog-to-digital converters.

3.1.9 Bird (or Angel) Clutter, the Constant Cross Section Radar

Bird flocks present a special clutter problem. They are best distinguished from aircraft by the size of the radar return. Figure 3-12 shows one measurement of the distribution of radar cross section of bird flocks. Small aircraft have a median cross section at their worst aspect angle of a little less than one square meter. From Figure 3-12 it may be seen the radar could be arranged so that the detection threshold was about 0.3 m^2 , then the majority of bird or angel clutter would be eliminated. This has been found to work in practice and is the basis for the R^{-4} law used for STC (sensitivity time control).

While the R^{-4} STC removes the range dependency in the radar's detection performance, it is also necessary to remove the detection variation with elevation angle. The zoom antenna should be used to accomplish this function.

A series of thresholding algorithms, developed by W. Goodchild at NAFEC, have been particularly successful in eliminating almost all of the angel and non-noiselike false alarms. These algorithms have been incorporated at NAFEC in the ARTS-III software at a point prior to the tracker.

The post-MTD thresholding algorithms as implemented at NAFEC are as follows:

- (1) The coverage is divided into $22.5^\circ \times 4$ nmi sectors.
- (2) From 0 to 16 nmi :
 - a. Prior to correlation and interpolation, replies are kept which exceed the sector threshold for its corresponding doppler filter.
 - b. Following correlation and interpolation 1.99 is added to the sector threshold of each filter which contains a single CPI report. (Nominal threshold is 0).
 - c. If no single CPI reports occur in a sector on the following scan(s), the threshold is decremented for each filter by $1/4$.
 - d. Single CPI reports passing the threshold test are sent to the tracker for possible track updating but not for track initialization.

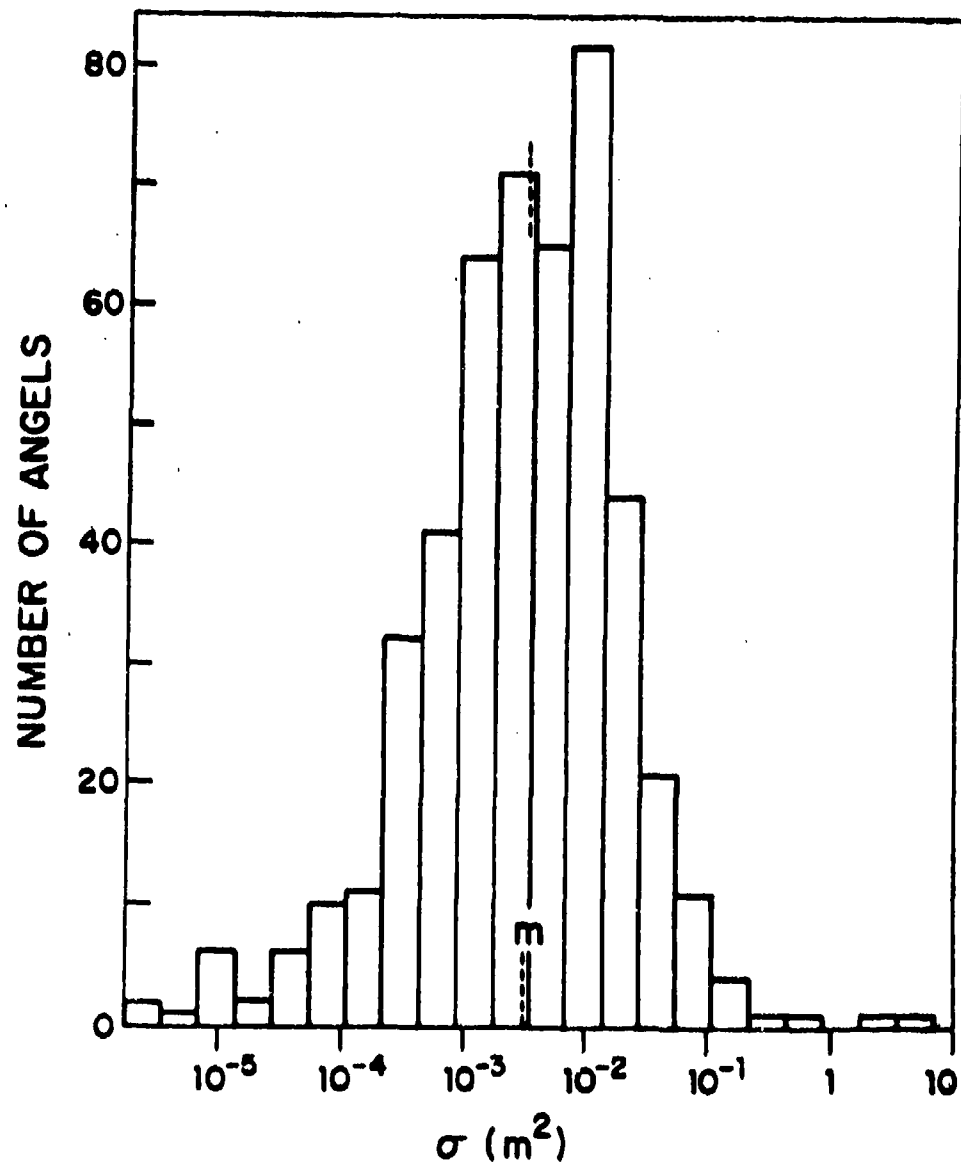


Figure 3-12. Histogram Showing how the Frequency of Occurrence of Angels Depends upon the Echoing Area σ (Reference 12)

(3) From 16 to 48 nmi:

- a. Correlation and interpolation is performed first.
- b. Single CPI reports are discarded if they do not exceed the threshold.
- c. Single CPI reports increment and lack of them decrement the threshold as above.
- d. Single CPI reports passing the threshold test, are sent to the tracker for either track updating or track initialization.

3.1.10 Pulse Compression

Pulse compression can be useful in an MTI radar when an increase in the average power is required to meet detection-in-noise requirements. Pulse compression is not particularly useful in reducing clutter if the pulse length is already moderately short.

Compare the performance of a system employing 13:1 pulse compression (from 7 to 1/2 μ sec) with one employing a simple 0.8 μ sec pulse. The expanded pulse contains 9.4 dB more power so that, properly processed, the radar can detect much smaller targets immersed in receiver noise. Against ground or rain clutter, however, the resolution of the radar is only 0.5/0.8 or 2 dB better. This is not a significant clutter improvement.

In addition, certain other difficulties arise with using pulse compression as described in Section 2.3.2.

3.2 Antenna Design Considerations

3.2.1 Elevation Beamwidth

Regardless of the particular type of elevation pattern desired, it is usually possible to identify a beamwidth requirement and this in turn determines the antenna vertical dimension. Some of the considerations which enter into this determination are altitude coverage at maximum range, and the rate of cut-off at the horizon. At S and L-band, aperture heights commensurate with 3° to 5° beamwidths (20 to 12 λ) appear to be adequate. This is the range of current ATC radars and barring a requirement for height-finding, there is no compelling reason to significantly deviate from it.

3.2.2 Azimuth Beamwidth

The azimuth beamwidth is determined by trading-off the number of pulses available for MTI processing and the angular resolution of the system. The range of interest lies between 1.7° and 2.5° (37λ to 25λ) as compared to less than 1.5° for current radars. Depending on the frequency, the "best" beamwidth may be biased in different directions because of other considerations.

At S-band, the narrower beamwidths are preferred because power is more of a problem. At L-band, the resulting antenna size, combined with the 15 RPM rotation rate, would tend to bias the preferred beamwidth toward the high side. This is probably the only azimuth-related antenna cost trade-off. In other words, there do not appear to be any implementation-related problems in accommodating whatever is required by the system. The beamwidths of interest are broader than those of current ATC radars which not only reduces antenna size, but also results in better multiple elevation beam performance.

3.2.3 Polarization

Polarization is an often neglected antenna characteristic in terms of an assessment of its impact on constraints and cost of antenna implementation. Through an evolutionary process, the polarization of the most recent FAA radars (ASR-8 and ARSR-3) has reached the ultimate in terms of capability. From a simple "black box" viewpoint, the antenna presents two ports which, depending on the state of a control device, are identified either as vertical/horizontal or RHCP/LHCP. The system, therefore, has the potential (not necessarily used) for complete dual diversity (for agility) or weather rejection/enhancement, respectively.

This level of capability implies that each radiating source (feedhorn or array element) include a switchable polarizer and a dual mode transducer. It is economically tolerable only for reflector configurations with at most several feedhorns. From a requirement viewpoint, it appears that the S-band option must have that level of capability because of the combination of need for rain rejection and rain display. At L-band, antenna-derived rain rejection is marginally not needed (assuming an MTD-like processor), this reduces the requirement to fixed single polarization and considerably simplifies the implementation

of a multiple beam configuration. At VIII there is, for all practical purposes, no rain to be rejected or displayed; hence, single polarization is adequate.

3.2.4 Antenna Sub-Systems

3.2.4.1 Rotary Joint

With polarization diversity or agility, two high power channels are required. At S-band, with high peak power and small size, this is a poor choice (the alternative of a high power switch above the rotary joint is no better). A better choice would be one high power channel and two low power channels. The latter are used for the two orthogonal polarizations in the "zoom" configuration, or for the high beam and weather return in the 2-beam system (ASR-8).

At L-band, the simplest acceptable radar configuration consists of a high power and a low power channel for transmission and reception, respectively, of a single polarization with a "zoom" feed. With the exception of the extra beacon channel and a lower power requirement, this would make it identical to the ARSR-2 joint. Polarization diversity requiring two high power channels is possible as far as the rotary joint is concerned, but practical only in the simple dual beam system (as in ARSR-3) since it would require duplication of the zoom feed system.

3.2.4.2 Pedestal Assembly

If the S-band option were selected, the pedestal is clearly sized by the much larger DABS antenna. For comparison, it would be very similar to those developed for stand-alone beacon antennas by Texas Instruments and Westinghouse as part of the ATCRBS antenna improvement program sponsored by DOT-TSC, the main differences being the absence of the synchronizing device and the increase in rotation rate to 15 RPM. For the L-band option, the radar antenna seems to be the dominant force. If an unspoiled reflector is used, either for zoom or fixed patterns, the system can still be operated without a radome and the pedestal is not markedly different from that necessary for the S-band option. With a spoiled reflector generating a fixed "thumb" pattern, there is a strong possibility that a radome would be needed since the vertical aperture would be at least double that of the multiple beam antenna (about 25').

3.2.5 Circular Array Considerations

Circular arrays with switch-commutated feeds were considered as candidate configurations for L-band and UHF. Constraints had to be imposed to keep cost at an acceptable level. The first constraint imposed was perfect azimuth focussing at only one elevation angle. This restricts the elevation coverage to about 20° while compromising the performance at low elevation angles. The elevation pattern is also fixed in transmit and receive. Because of the high aperture cost factor the antenna vertical aperture was restricted to 8' at L-band and 16' at UHF, thereby limiting the achievable gain. As a consequence of this gain, reduction and the additional losses in the commutating feed, the required pulse power levels are such as to dictate the use of pulse compression at L-band and possibly UHF with the inherent problems and cost.

Apertures needed to satisfy the resolution requirement cause a conventional circular array to fail to compete with a rotating reflector. Furthermore, the relative performance is degraded by the absence of elevation pattern flexibility.

3.3 Alternative Radar Systems Considered

A number of alternative radar systems were considered. Frequencies were chosen between S-band and UHF from those already available to the FAA or those which are allocated for radiolocation ⁽¹¹⁾ within the United States, and so might be made available for ASR service. The alternative radar designs are listed in Table 3-1. Higher frequencies were not considered because of the known problems brought on by rain attenuation and backscatter.

In each frequency band various combinations of features were chosen which would fulfill all of the operational requirements. This resulted in eight alternative radars as listed in Table 3-2. A one-square-meter, Swerling Case I, target was assumed. Two types of polarization, linear (L) and circular (C), were assumed at S-band, but linear was judged to be adequate at L-band. With advanced signal processing used in a new radar, linear polarization at L-band would give about the same rain rejection as circular polarization (CP) does at S-band. In addition, advantage is taken of the large specular return

TABLE 3-1
LIST OF RADAR ALTERNATIVES CONSIDERED

ANTENNA

RADAR	FREQUENCY	TYPE	EL.	Az.	SIZE W x H (FT)	GAIN (NET)
ASR-8 (12.5 RPM)	2700-2900 MHz	ROTATING REFLECTOR	4.8° csc² 30°	1.4°	17 x 9	33.5
ASP() (15 RPM)	3500 - 3700	ROTATING REFLECTOR	3.3° ZOOM (OR THUMB)*	2.25°	6.0 x 5.2(13)*	32.8
				1.7°	10 x 5.2(13)*	34.0
	2700 - 2900	ROTATING REFLECTOR	3.3° ZOOM (OR THUMB)*	2.25°	9.9 x 6.7(16.7)*	32.8
				1.7°	13 x 6.7(16.7)*	34.0
L-1 L-2	1250 - 1350	ROTATING REFLECTOR	3.3° ZOOM	2.25°	21.2 x 14.5	32.8
				1.7°	28.1 x 14.5	34.0
L-C	1250 - 1350	CYLINDRICAL+ ARRAY (MONOPULSE)	3.3° THUMB	2.4°	32.2 x 14.5	28.5**
UHF-C	420 - 450	CYLINDRICAL+ ARRAY (MONOPULSE)	10° THUMB	2.4°	70.1 x 14.4	24.5**

*Antenna with thumb pattern is 2.5 times larger in the vertical dimension than the antenna with zoom feature.

**At antenna input; includes 5 dB cable loss for L-C and UHF-C

+ Step-scan (variable scan rate)

TABLE 3-2 ALTERNATIVE RADAR DESIGNS

ASR-(C)

	ASR-8	S _H -2	S _L -2	L-2	S _H -1	S _L -1	L-1	L-C	UHF-C
• ANTENNA									
AZIMUTH BEAMWIDTH	ROTATING	ROTATING	ROTATING		ROTATING			STEP-SCAN	
RPM (SCAN RATE)	1.4°	2.25°	1.7°		1.7°			2.4°	
PRF	12.5	15	15		15			15 (VARIABLE)	
PULSES PER DWELL	1030	1100-1360	1100-1360		1100-1360			1100 - 1360	
NET GAIN (DB)	19	28-34	21-26		21-26			32	
ELEVATION PATTERN	33.5	32.8	34		34			28.5	24.5
POLARIZATION (LP-Linear CP-Circular)	4.8° CSC ²	3.3° ZOOM	3.3° ZOOM		3.3° ZOOM			3.3° thumb LP	10° thumb LP
• LOSSES: (DB)	LP,CP	LP,CP	LP,CP	LP	LP,CP	LP,CP	LP		
FIELD DEGRADATION	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
TRANSMIT	2.5	2.5	2.5	1.8	2.5	1.8	1.0	1.0	1.0
RECEIVE (DB)	4.0	4.0	4.0	3.3	4.0	3.3	2.5	2.5	2.0
ATMOSPHERIC (2-WAY)(DB)	1.0	1.0	1.0	0.8	1.0	0.8	0.8	0.8	0.3
CIRCULAR POLARIZATION (DB)	2.0	2.0	2.0	--	2.0	--	--	--	--
TOTAL	12.5	12.5	12.5	8.9	12.5	8.9	7.3	7.3	5.3
• SIGNAL PROCESSING	MTI(3)	MTI(3) + FFT(8) + MLT + GCM	MTI(3) + FFT(8) + MLT + GCM		MTI(3) + FFT(8) + MLT + GCM			FFT(8) + MLT + PC	
BLIND SPEED (KNOTS)	107	91 113	113 146	254 314	91 113	113 146	254 314	254 314	760 950
RANGE (PEAK OF BEAM) NM/I	39	51	51	51	51	51	51	51	51
RECEIVER NOISE FIGURE (DB)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
ANTENNA TEMPERATURE (DEG)	100	100	100	100	100	100	100	100	100
IF SNR, P _D =0.75, P _{FA} =10 ⁻⁵	11.1	8.7	8.7	8.7	9.4	9.4	9.4	4.1	4.1
PULSE LENGTH(μSEC)	0.6	1.0	1.0	1.0	1.0	1.0	1.0	13	13
• TRANSMITTER POWER									
CP	1.58	3.6	2.20		2.4	1.48			
PEAK MW	0.95	5.0	3.0		3.3	2.00			
AVG. KW									
LP	1.0	2.3	1.4	0.196	1.5	0.94	0.132	0.330	0.016
PEAK MW									
AVG. KW	0.6	3.1	1.9	0.266	2.1	1.28	0.13	0.53	0.282

from the side of the aircraft. Such return (perhaps 100 m^2) for some small aircraft is lost when using CP (see Appendix A). Another advantage of linear polarization is simplification of the circuits required for collecting weather data. A separate antenna output, rotary joint path and receiver are eliminated. In addition, any shift in boresite due to the use of CP is eliminated. Use of L-band and horizontal polarization permits simple integration of the beacon antenna for optimum performance.

A circular polarization loss of 2 dB is included where CP is used. Some interpretations of the available cross section for small aircraft would place this at closer to 5 dB (see Appendix A).

The ASR-8 is included in Table 3-2 for completeness. In this table, MTL refers to mean-level thresholding, GCM to ground clutter map; and PC to pulse compression.

The vertical coverage for 1 and 10 m^2 target cross sections is shown in Figure 2-1, together with the requirements derived in Section 2. Notice that higher altitude, longer range coverage is provided for larger aircraft (10 m^2).

Appendix C describes the methods used to arrive at the signal processing losses. The IF SNR (signal-to-noise ratio) in Table 3-2 includes the effect of any signal processing losses.

Except for the ASR-8, the required transmitter powers (near the bottom of Table 3-2) were calculated using the data in the column above each one. For the ASR-8 the rated power was employed to calculate the range on the one-square-meter target at the peak of the antenna beam, assuming linear polarization was to be employed.

3.4 Radar Costs

Table 3-3 lists the estimated costs of the candidate radars. In estimating these costs it has been assumed that the radar is to be added to an automated terminal system. This assumption strongly influences the antenna costs. It has been assumed that the antenna (e.g. DABS) is approximately 25-ft. wide by 8-ft. high and mounted on a rigid pedestal and tower. For the rotating antenna cases in Table 3-3, we assume a separate radar antenna mounted back-to-back with the DABS antenna. In this case, the radar antenna cost includes the reflector feed, its

TABLE 3-3

INITIAL RADAR COSTS (Thousands of Dollars)
Production Buy of 25

	<u>ASR-8</u>	<u>S_H-2</u>	<u>S_L-2</u>	<u>L-2</u>	<u>S_H-1</u>	<u>S_L-1</u>	<u>L-1</u>	<u>L-C</u>	<u>UHF-C</u>
Antenna	45	90	90	110	100	100	120	260	380
Transmitter/Receiver (Dual)	180	250	250	150	220	220	150	80	70
Signal Processor (Dual)	100	120	120	120	120	120	120	120	120
Integration & Miscellaneous	50	50	50	50	50	50	50	50	50
TOTAL	375	510	510	430	490	490	440	510	580

support structure and added channels in the rotary joint. For the L-band and UHF radars utilizing electronically step-scanned antennas the cost includes that of the entire antenna and its support structure. It is principally the high cost of this separate antenna system that makes these radars unattractive.

To add a radar at a DABS site would require costs as outlined in Table 3-4. Here, Radar L-2 has been selected as the example for costing. At the bottom of the table the capital outlay amortization cost per year is calculated based on a 10% interest rate and a 15-year equipment lifetime.

Finally, Table 3-5 enumerates the annual costs involved with adding a radar to a DABS system. It is estimated that a modern terminal control system including radar, beacon and ARTS-III equipment would initially cost \$2M and the annual cost with equipment amortized over 15 years, including all operating costs would be \$692K. The radar portion of this cost (\$169K) (Table 3-5) is about 24% of this cost.

TABLE 3-4

**CAPITAL OUTLAY
(RADAR L-2)**

RADAR	\$430, 000
TEST EQUIPMENT	30, 000
PROVISIONING AND INSPECTION (32%)	147, 000
REGIONAL INSTALLATION COSTS	50, 000
RADAR BUILDINGS	30, 000
SHIPMENT AND INSTALLATION	100, 000
	<u>\$787, 000</u>
Cost per year amortized at 10% over 15 years (13. 147%)	\$ 103, 000

TABLE 3-5

ANNUAL COST OF RADAR

MAINTENANCE PERSONNEL (2.48 man yrs/yr at \$20, 975/man yr)	\$ 52, 020
SPARE PARTS ATTRITION (at \$100/failure plus \$0.50/hr for Klystron MUT - 300 Hrs)	7, 330
AMORTIZATION OF CAPITAL OUTLAY	103, 000
UTILITIES AND LEASES, ETC.	6, 800
HOURLY COST: \$19.20/hr	<hr/> \$169, 150

4.0 CONCLUSIONS

Of the radar design candidates listed in Table 3-2, the most attractive for the ASR-() application is the L-band design designated as L-2. Design parameters of this radar are repeated in more detail in Table 4-1. A modified ASR-8 providing better weather performance at S-band and existing hardware should be considered as a runner-up.

4.1 Advantages of the Proposed L-band Radar Design

This version of the ASR-() radar was chosen for the following reasons:

4.1.1 Low Transmitter Power

The L-band radar requires about 10 dB less transmitter power than the corresponding S-band radar. This follows since a larger antenna is employed, waveguide and RF component losses are lower and linear polarization is used rather than circular to take advantage of the larger target cross section. The resulting power level at L-band (200 kW) is more easily obtained and much less expensive than the high power level (2 MW) required at S-band.

4.1.2 Weather Output

The weather performance of an ASR-() operating at S-band would be decidedly better than one operating at L-band. Increasing emphasis by the FAA on weather and turbulence detection and avoidance may cause this reason for staying at S-band to govern.

If S-band were used, an extra channel in the rotary joint would be required to bring down weather data. If a UHF radar were selected, weather data would not be available.

At L-band use of linear polarization would permit use of a simpler less expensive antenna feed. A single receiver channel could be used for aircraft detection and for monitoring precipitation clutter.

4.1.3 Beacon Compatibility

With a 2.25-deg beamwidth, the L-band antenna will be about the same size as that required for DABS so that when they are mounted back-to-back there should be little extra wind loading. An alternative arrangement would be to use a common feed system for radar and beacon.

TABLE 4-1
PARAMETERS OF RECOMMENDED RADAR

WAVEFORM:	1250 TO 1350 MHz
FREQUENCY	1 μ SEC
PULSE LENGTH	ALTERNATING GROUPS OF 10 PULSES AT 1100 AND
WAVEFORM	1360 Hz PRF
ANTENNA:	3.3° ZOOM TO 15,000 FT (FIGURE 2-1)
ELEVATION COVERAGE	2.25°
AZIMUTH BEAMWIDTH	15
RPM	LINEAR
POLARIZATION	22 x 14.5 FT
SIZE	
TRANSMITTER/RECEIVER:	
PEAK POWER	200 kW
AVERAGE POWER	270 W
RECEIVER NOISE FIGURE	1.25 DB
SIGNAL PROCESSING:	MTD DIGITAL DOPPLER FILTERING, MEANLEVEL THRESHOLDING, GROUND CLUTTER MAP, INTRA- AND SCAN-TO-SCAN CORRELATION
OUTPUT FORMAT:	DIGITAL TARGET REPORTS, ONE PER AIRCRAFT PER SCAN

The 2-ft. antenna has the correct width and, in addition, one sense of linear polarization (horizontal) could be used for radar while the vertical polarization is used for beacon.

4.1.4 Minimizes Antenna Cost

For this application, the rotating antenna is more economical than the electronically step-scanned cylindrical antenna. In addition, coverage above 20° in elevation would complicate its design, and a separate beacon antenna would be required. In addition, a rotating antenna could incorporate "zoom" capability.

4.1.5 Excellent Clutter Performance

The signal processing recommended is similar to the MTD processor which has demonstrated superior automatic aircraft acquisition and tracking performance even in heavy ground and weather clutter. (13, 14) With the MTD, false alarms due to ground and weather clutter occur at a very low rate, thus avoiding the difficulties experienced using sliding window detectors.

4.1.6 Good Angel Performance

The use of the zoom antenna and the proper STC to produce a constant cross section antenna would eliminate most angel clutter. Scan-to-scan correlation would solve the rest of this problem.

4.1.7 Overcomes Mutual Interference

Although there is only 50 MHz of available bandwidth at L-band, as opposed to 200 MHz at S-band, interference rejection techniques incorporated in the MTD permit nearby radars in the same band to function without performance degradation.

4.1.8 Anomalous Propagation

Use of constant prf, so that groups of pulses may be coherently processed, and a fully coherent transmitter would overcome excess clutter return due to anomalous propagation conditions and second-time-around radar clutter. Multiple prf's make second-time-around aircraft returns easy to recognize.

4.2 Use of Modified ASR-8

A comparison of the ASR-8 (Column 1) with $S_L - 1$ (Column 6) in Table 3-2 indicates that if the pulse length of the ASR-8 were increased from 0.6 to 1.0 sec, its prf increased about 20% and modern coherent processing employed, ASR-8 performance would be adequate both in clutter and noise when using linear polarization. With these changes the range would be increased from 39 nmi to about 51 nmi. During rain, however, when circular polarization is employed, the maximum range would be about 45 nmi. This still would be adequate for most operational situations. Thus, because ASR-8 radars are now in production, and because of the increased emphasis upon weather and turbulence detection, our second choice would be the development of modifications for the ASR-8 to increase its pulse length and prf, to add modern coherent processing and to add a weather channel.

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APPENDIX A

RADAR TARGET CROSS SECTION DATA

A.1 INTRODUCTION AND SUMMARY

Since an air traffic control radar must provide surveillance against all aircraft within its required coverage volume, a small general aviation aircraft was chosen as limiting for defining performance. In Reference 15, three representative general aviation aircraft were measured on a test range at the Holloman Air Force Base Radar Target Scatter (RATSCAT) facility. Each was a small single engine aircraft: a Cessna 150L (all metal, high wing), a Piper Cherokee 140 (all metal, low wing) and a Super Cub (metal framed, fabric covered). The purpose of this appendix is to summarize the results of these measurements and to define an appropriate target model for related range performance calculations.

It is concluded that a one square meter, Rayleigh fluctuating (Swirling Case I or II) target is an appropriate model for small general aviation aircraft in terminal airspace when using linearly polarized radiation. For circular polarization, a loss of 2 dB is appropriate.

A.2 DATA

The reference provides data for L-, S-, and C-bands at horizontal, vertical, and circular polarization. Frequencies under consideration for a new ASR-() are 1.25 GHz (L-band) and 2.8 GHz (S-band). The L-band data was taken only for 0° roll and 0° pitch. However, roll and pitch variations at S-band were greatest for the broadside aspect angles (90° and 270°) where the radar cross section tends to be large, hence consideration of only the 0° roll 0° pitch case should provide conservative results.

Figure A-1 shows the probability distribution function of the Piper Cherokee 140 for vertical (VV) and horizontal (HH) polarization at L- and S-bands, and for right-circular (RR) polarization at S-band. These curves were obtained by expanding dividers along raw data plots of radar cross section versus azimuth in the reference. Figure A-1 shows:

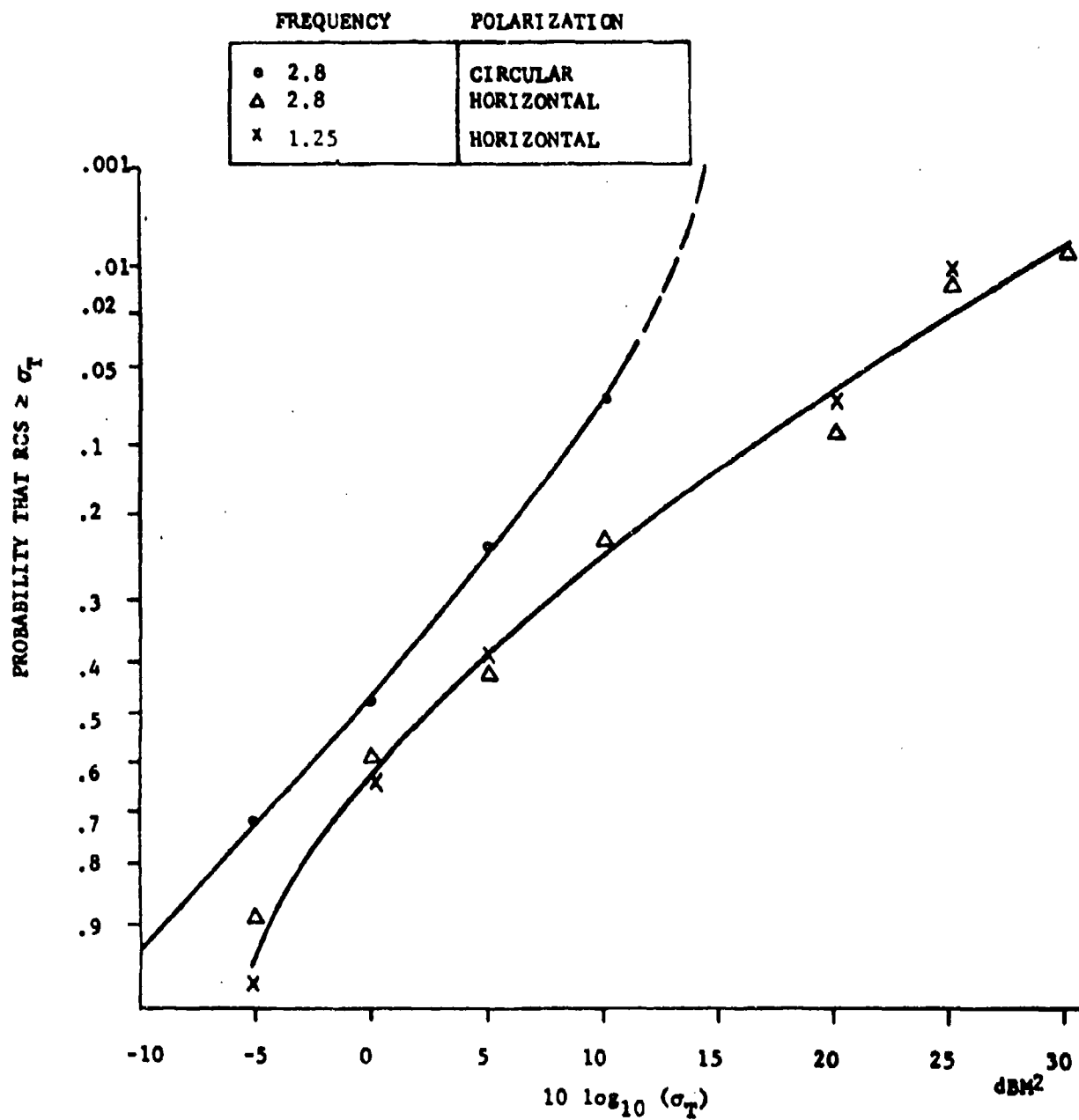


FIGURE A-1 RADAR CROSS SECTION DISTRIBUTION FOR PIPER CHEROKEE 140
OVER ALL ASPECT ANGLES (0° PITCH, 0° ROLL)

- a) negligible difference between L- and S-band radar cross section distributions for horizontal polarization, with a median value of about 1m^2 .
- b) A loss for circular polarization (at S-band) of about 3 dB, resulting in a median value of about 0.5m^2 .

Figures A-2 and A-3 are polar plots of median radar cross section as a function of aircraft aspect angle (azimuth) for the same Piper Cherokee 140 aircraft at L- and S-band. The median values were calculated by RATSCAT over 10° intervals, and are for the 0° pitch, 0° roll condition. Several interesting points can be made from these plots:

- a) Within $\pm 50^\circ$ of the nose or tail aspects, vertical polarization at S-band produces a slightly larger median cross section than horizontal polarization, while at L-band, both polarizations produce about the same results as S-band horizontal polarization (Figure A-1).
- b) Within $\pm 20^\circ$ of broadside both linear polarizations (S- and L-band) produce about the same results. However, circular polarization reduces the S-band radar cross section by about 12 dB.
- c) At S-band, circular polarization produces losses at all aircraft aspect angles, the loss being greater for vertical than for horizontal polarization.

The 12 dB broadside loss for circular polarization is particularly unfortunate because aircraft flying tangential courses do not have the benefit of MTI cancellation in rain. One would, therefore, expect better performance from an L-band radar (which does not require circular polarization for rain rejection) than from an S-band radar with circular polarization for tangential targets.

Table A-1 provides numerical values for the median radar cross section data plotted in Figures A-2 and A-3 for the Piper Cherokee 140. Values for L-band circular polarization were included for completeness, although circular polarization was considered unnecessary for rain rejection at L-band. Median values are shown for the full 360° and for the nose-on $\pm 5^\circ$ and $\pm 50^\circ$ aspects.

—	2.8 GHz	CIRCULAR
- - -	2.8	HORIZONTAL
- - -	1.25	HORIZONTAL

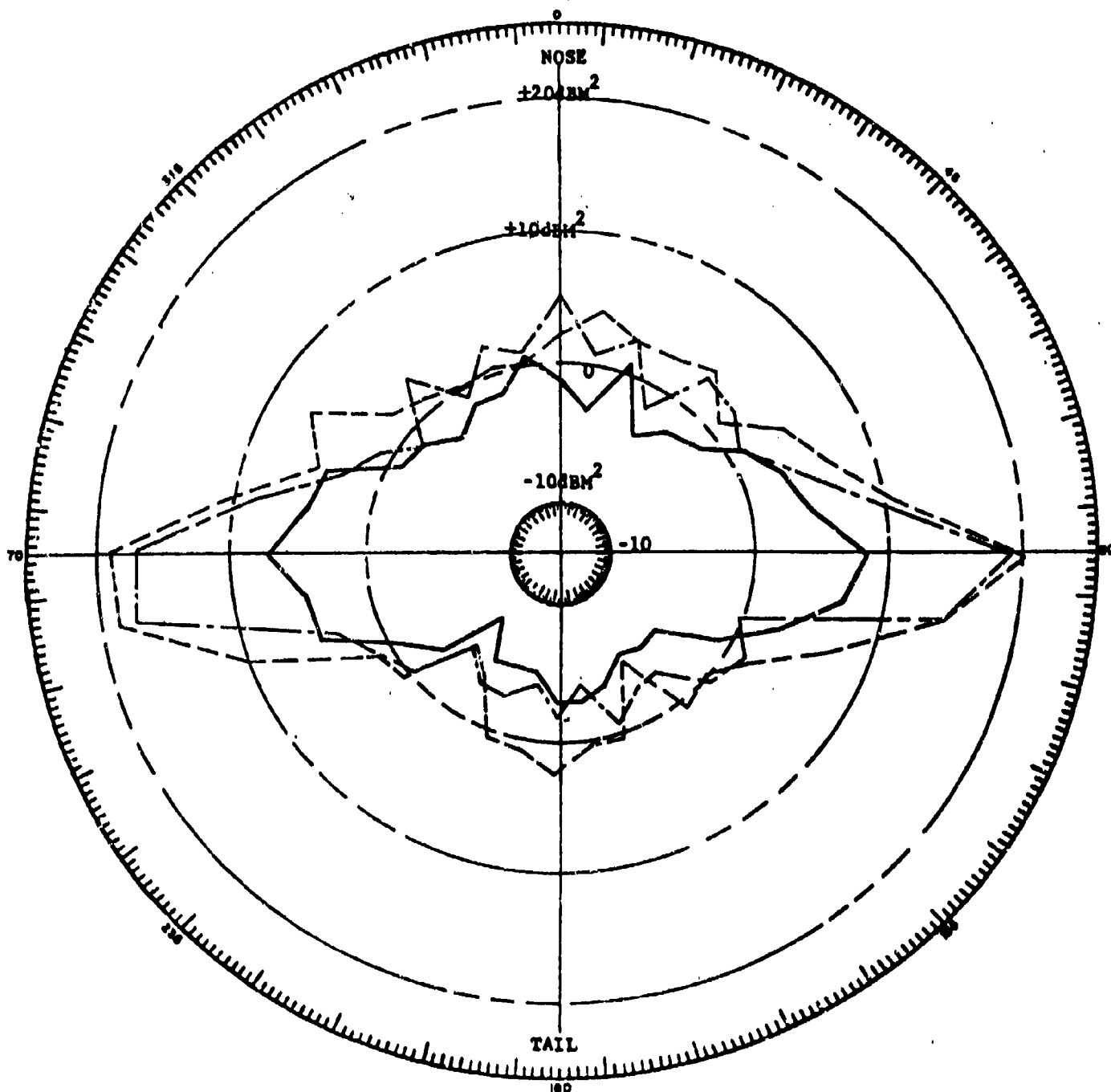


FIGURE A-2 PIPER CHEROKEE 140 MEDIAN RADAR CROSS SECTION (dBm²)
VERSUS AIRCRAFT ASPECT ANGLE

FREQUENCY	POLARIZATION
—	2.8 GHz CIRCULAR
---	2.8 VERTICAL
-.-	1.25 VERTICAL

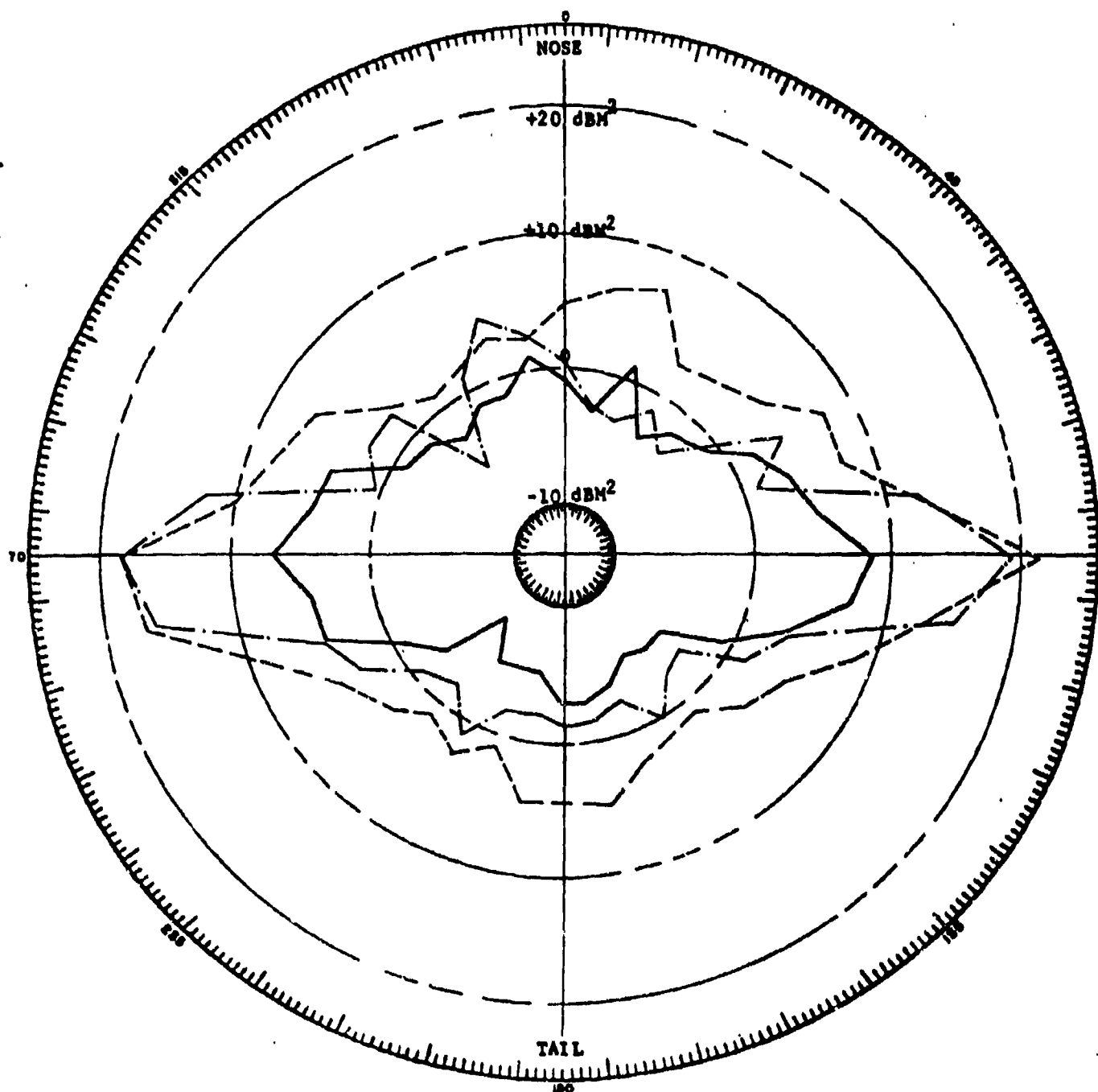


FIGURE A-3 PIPER CHEROKEE 140 MEDIAN RADAR CROSS SECTION (dBm^2)
VERSUS AIRCRAFT ASPECT ANGLE

TABLE A-1

MEDIAN RADAR CROSS SECTION (SQUARE METERS) FOR PIPER CHEROKEE 140

0° PITCH, 0° ROLL

RANGE OF ASPECT ANGLES	360°		NOSE +50°		NOSE +5°	
	1.25 GHz	2.8 GHz	1.25 GHz	2.8 GHz	1.25 GHz	2.8 GHz
FREQUENCY						
HORIZONTAL POL.	1.3 M ²	1.7 M ²	1.5 M ²	1.6 M ²	3.5	1.8 M ²
VERTICAL POL.	1.25	2.8	.85	2.2	1.1	3.3
CIRCULAR POL.	1.1	0.69	1.3	0.68	0.91	0.78

TABLE A-2

MEDIAN RADAR CROSS SECTION (SQUARE METERS) FOR THREE AIRCRAFT

0° PITCH, 0° ROLL, NOSE +50° ASPECT

AIRCRAFT	PIPER CHEROKEE 140		CESSNA 150		PIPER SUPER CUB	
TYPE	LOW WING, METAL SKIN		HIGH WING, METAL SKIN		HIGH WING FABRIC COVERED METAL FRAME	
FREQUENCY	1.25 GHz	2.8 GHz	1.25 GHz	2.8 GHz	1.25 GHz	2.8 GHz
HORIZONTAL POL.	1.5 M ²	1.6 M ²	1.1 M ²	1.3 M ²	1.6 M ²	.91 M ²
VERTICAL POL.	.85	2.2	1.3	1.3	3.2	3.2
CIRCULAR POL.	1.3	0.68	0.66	1.7	1.1	1.7

Results can be summarized as follows:

- a) For horizontal polarization, there is little difference between L- and S-band. Radar range differences are less than 7% over 360° and 1% for within $\pm 50^\circ$ of the nose-on aspect.
- b) For vertical polarization, S-band produces a higher median radar cross section than L-band. Radar range improvement is 20-26%.
- c) Circular polarization reduces the S-band medians by 4-6 dB over 360° and 4-5 dB for the nose $\pm 50^\circ$ aspects.
- d) There is no significant difference between the 360° medians and the $\pm 50^\circ$ medians for linear polarization.
- e) Nose-on $\pm 50^\circ$ medians are larger than the medians for larger ranges of aspect angles for most cases.

Table A-2 provides similar data for all three aircraft for the nose-on $\pm 50^\circ$ range of aspect angles. Interesting differences are:

- a) The high wing aircraft tend to favor vertical polarization and have the same medians at L- and S-bands.
- b) The metal frame of the fabric-covered Super Cub enhances its reflectivity relative to the metal-skinned aircraft except at S-band with horizontal polarization.
- c) Circular polarization at S-band provides a gain in median radar cross section for the Cessna 150. For the Super Cub, circular polarization produces a gain of 2.7 dB over horizontal and a loss of 2.8 dB relative to vertical polarization.
- d) Vertical polarization provides better performance for all cases except for the Cherokee 140 at L-band.

Comparison of the median cross section computed for $\pm 5^\circ$ from the nose-on aspect with the data from Table A-2 (nose on $\pm 50^\circ$) shows that the $\pm 5^\circ$ median is larger than the $\pm 50^\circ$ median for all cases except L-band circular polarization for the Super Cub and the Cherokee 140. The average increase is 2.9 dB at S-band and 3.6 dB at L-band. The nose-on $\pm 50^\circ$ case produces comparable results to the tail-on $\pm 50^\circ$ aspects.

A.3. RESULTS

A.3.1 Median Radar Cross Section

For the three aircraft, there is no clear trend in median cross section data as a function of frequency of polarization. Although it is

reasonable to assume that all aircraft aspects are equally likely for surveillance at long range, it is appropriate to exclude the large returns at broadside $\pm 40^\circ$ from the model used in radar performance calculations in order to ensure a reasonably conservative design. The nose-on $\pm 50^\circ$ range of aspect angles is, therefore, appropriate for defining the target model used in performance computations.

Assuming that the three aircraft considered here are a reasonable sample of small general aviation aircraft, and that the smallest should be detectable at maximum range, an appropriate radar cross section for linear polarization at L- and S-bands is one square meter. Comparing this value with the smallest medians, the errors are +0.7 and -0.4 dB at L-band and +0.4 and -1.1 dB at S-band. The corresponding radar range variations are 2 to 6%. For circular polarization at S-band, a loss of 2 dB relative to one square meter (0.63m^2) is appropriate.

A.3.2 Extensions to UHF and High S-bands

The available RATSCAT data does not consider the high S-band (3.5 - 3.7 GHz) and UHF (0.43 GHz) frequencies considered in the radar studies. Consequently, the same one square meter radar cross section was used for high S- and UHF bands. In the case of UHF, this is a poor assumption, and the resulting radar calculations have a higher degree of uncertainty. Until comparable measurements are made on the same aircraft at UHF, it is difficult to state whether a one square meter cross section at UHF is conservative or not since the radar wavelength (0.7 m) is comparable in size to a number of the individual scatters in the aircraft structure.

A.3.3 Fluctuation Statistics

A fluctuation model is necessary to relate measured radar cross section data to the probability of detection on a given scan, since the probability of observing a given cross section on each scan must be computed. The most widely used fluctuation model for aircraft targets is the Rayleigh model, which assumes that the aircraft behaves as a random assembly of scatters, no one of which is dominant. The resulting probability density function for the input signal-to-noise power ratio is exponential:

$$W(X, \bar{X}) = \frac{1}{\bar{X}} e^{-\frac{X}{\bar{X}}}, \quad X \geq 0 \quad (A-1)$$

where X = input signal-to-noise (power ratio), and

\bar{X} = average value of X over all target fluctuations

Using this expression, Swerling (17, 18) has computed detection probability curves which relate false alarm rate, detection probability, and signal-to-noise ratio for two cases. Swerling Case 1 assumes that the radar cross section remains constant on any given scan of the radar, but fluctuates independently from scan to scan, while the Swerling Case 2 model assumes that the radar cross section varies independently from pulse to pulse as well as from scan to scan. The Case 1 model is applicable to fixed frequency radars since the target aspect angle changes little during the few milliseconds that the radar beam illuminates the target. The Case 2 model is appropriate if the radar frequency is changed from pulse-to-pulse by an amount Δf sufficient to decorrelate the target:

$$\Delta f = 150/L \text{ in MHz} \quad (A-2)$$

where L is the target in meters. Assuming a 10 meter length for small aircraft, 15 MHz of pulse to pulse frequency agility should be sufficient to change the target from Case 1 to Case 2. Pulse-to-pulse polarization agility may also have a similar effect in some cases.

In order to check the assumption of Rayleigh fluctuations with the measured radar cross section data, cumulative distributions of radar cross section for the Piper Cherokee 140 were extracted from the raw data for the nose-on $\pm 50^\circ$ range of aspects. Figures A-4 and A-5 compare the S-band and L-band data points (respectively) with the Rayleigh fluctuation model (Equation A-1) for a one-square meter mean cross section. Straight-line fits to the data points produce a slope that is essentially the same as the dotted line for the Rayleigh model, indicating that use of this model is valid for the Piper Cherokee 140 within $\pm 50^\circ$ of the nose-on aspects. The data points are below the Rayleigh line because the mean radar cross sections of the Cherokee are larger than the one square meter value used for the Rayleigh line. It should also be noted that the S-band median (50%) cross sections in Figure A-4 are slightly different from the RATSCAT printout medians tabulated in Table A-1;

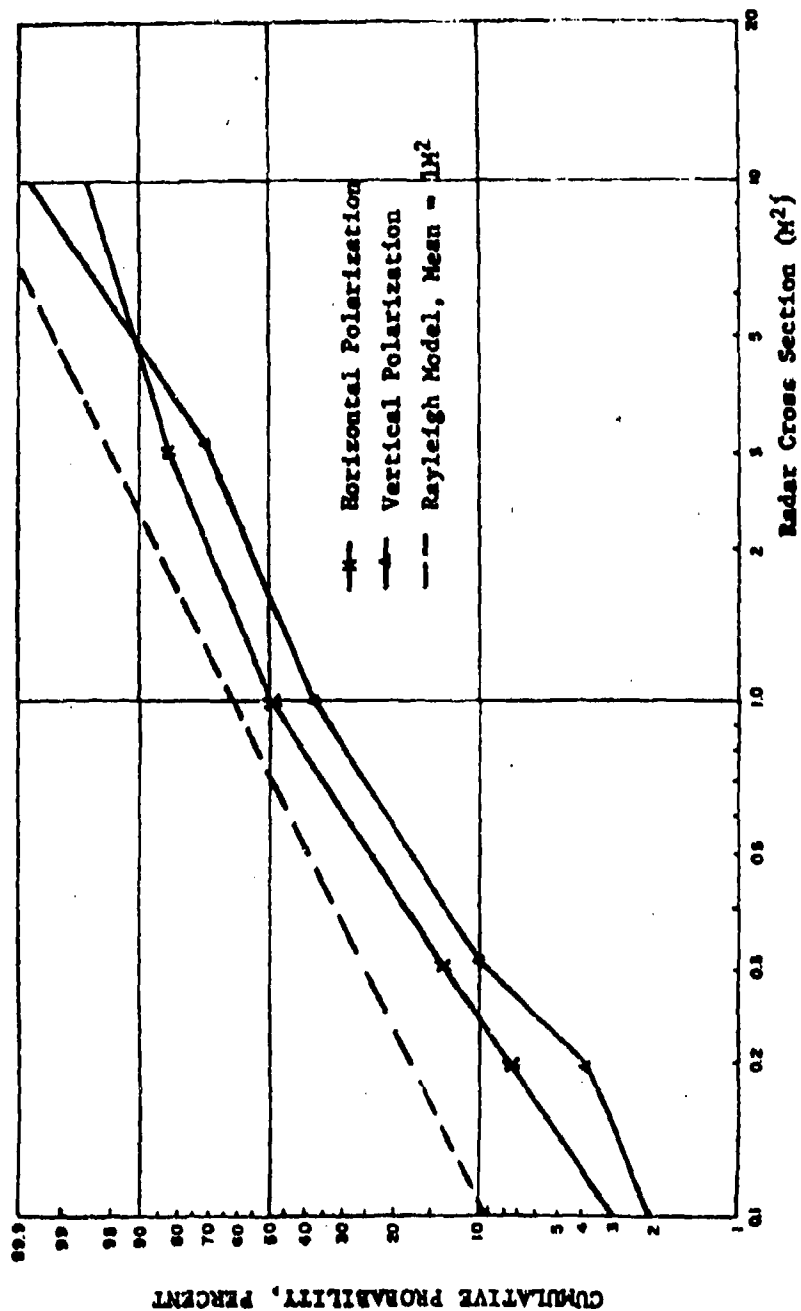


FIGURE A-4

COMPARISON OF PIPER CHEROKEE 140 S-BAND CROSS SECTION DISTRIBUTIONS
WITH RAYLEIGH MODEL FOR NOSE-ON $\pm 50^\circ$ ASPECTS

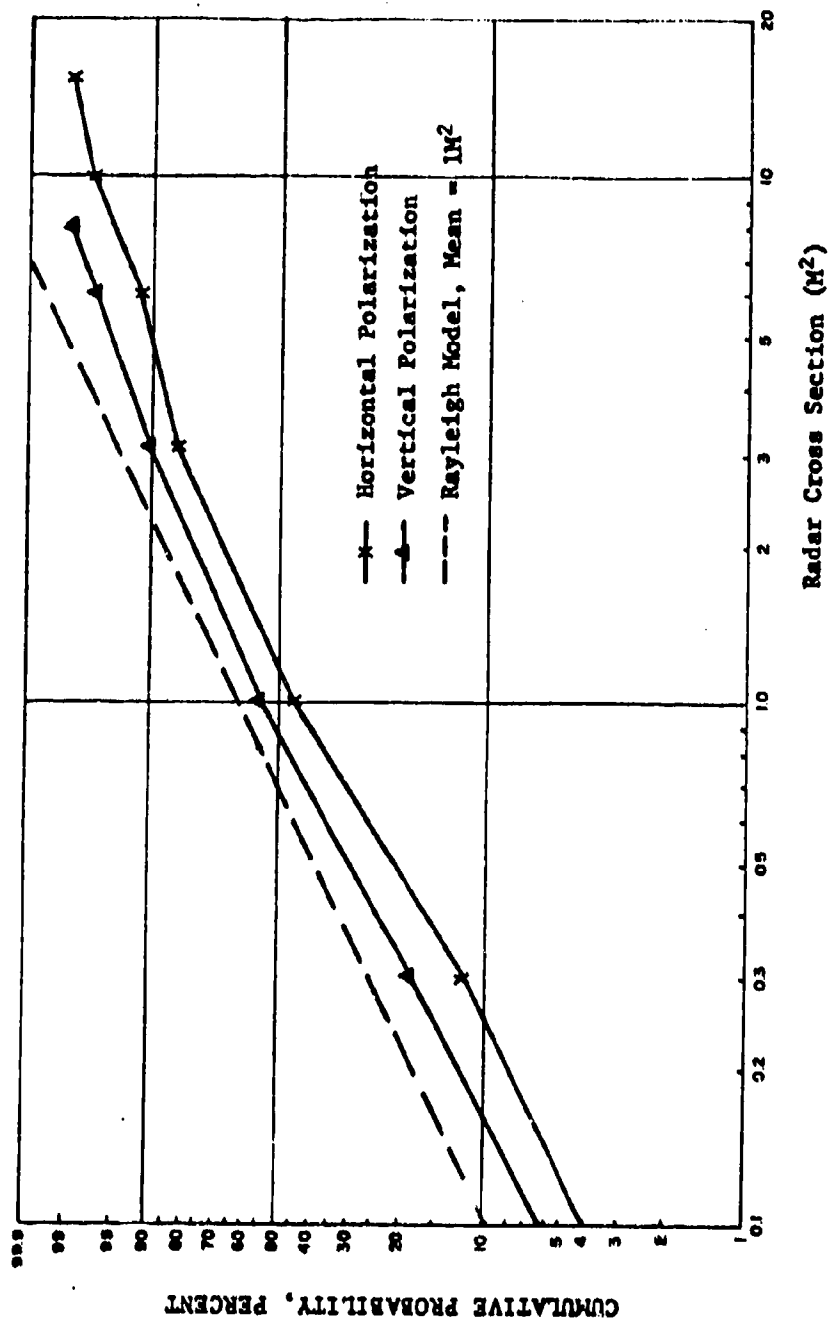


FIGURE A-5

COMPARISON OF PIPER CHEROKEE 140 L-BAND CROSS SECTION DISTRIBUTIONS
WITH RAYLEIGH MODEL FOR NOSE-ON $\pm 50^\circ$ ASPECTS

this inaccuracy is not unexpected since the data in the figure was obtained by expanding dividers across the raw data plots, which contain very many close-spaced peaks and nulls.

The Rayleigh fluctuating target model (Swerling Case 1 and Case 2 detection probability statistics) is therefore appropriate for aspects of interest (those excluding large cross sections near broadside) to the Radar studies. Since Swerling's work used the average signal-to-noise power ratio (Equation A-1), the mean radar cross section is the appropriate value to use in the radar equation. For the Rayleigh target, the mean corresponds to the 63rd percentile value and is 1.44 times (1.6 dB) larger than the median. Because of the inherent uncertainties in radar cross section measurements, this correction factor is often justifiably ignored. In a free space environment, radar detection range predictions are about 10% conservative if the median, rather than the mean, cross section is used.

A.3.4 T-33 Data

Similar radar cross section measurements ⁽¹⁶⁾ on a small, twin engine, military jet trainer (T-33) also reported good agreement with a Swerling Case 1 model for the $\pm 60^\circ$ sector about the nose of the aircraft. For S-band, using vertical polarization, the median cross section was 0.68 m^2 .

ACQUISITION LOGIC PERFORMANCE

An earlier section described the functions of the scan-to-scan correlator. In this Appendix, two examples of aircraft acquisition logic which meet most of these requirements are presented. The results were derived from steady-state Markov analysis of the two sample logics; a more thorough evaluation of alternative schemes is recommended before the final acquisition logic is selected.

Steady-state probabilities were derived for three target report validity levels. The highest validity level considered here is referred to as the "firm track" level; all other validity levels are lumped together in this analysis as "tentative tracks". In practice, there would be a number of different categories of tentative tracks, each representing different validity levels and/or particular cases such as non-moving fixed-point clutter targets, etc.

Acquisition Logic A initially promotes a target to the firm track level if any two out of three radar scans produce a correlated target report, that is, a report which falls within the predicted target position window on a particular scan. A predicted doppler window may also be utilized when the radar measures target doppler. The target report is dropped if no correlated report occurs for seven consecutive scans. A Markov state diagram for this logic is shown in Figure B-1. States 4-10 refer to the "firm track" level, states 2 and 3 refer to "tentative track" level and state 1 refers to "no track" or drop track level. p_d equals the probability of detection and p equals the probability of successful correlation. The latter requires that the target is detected in the predicted target window.

$$q_d = 1 - p_d \text{ and } q = 1 - p.$$

Acquisition Logic B is a two step logic whose state diagram is shown in Figure 3-2. Initially, a detection and successful correlation are required within 3 consecutive scans. When this criterion is met, the logic requires only one report within the next three scans. When both of these criteria are met, the target enters the firm track status

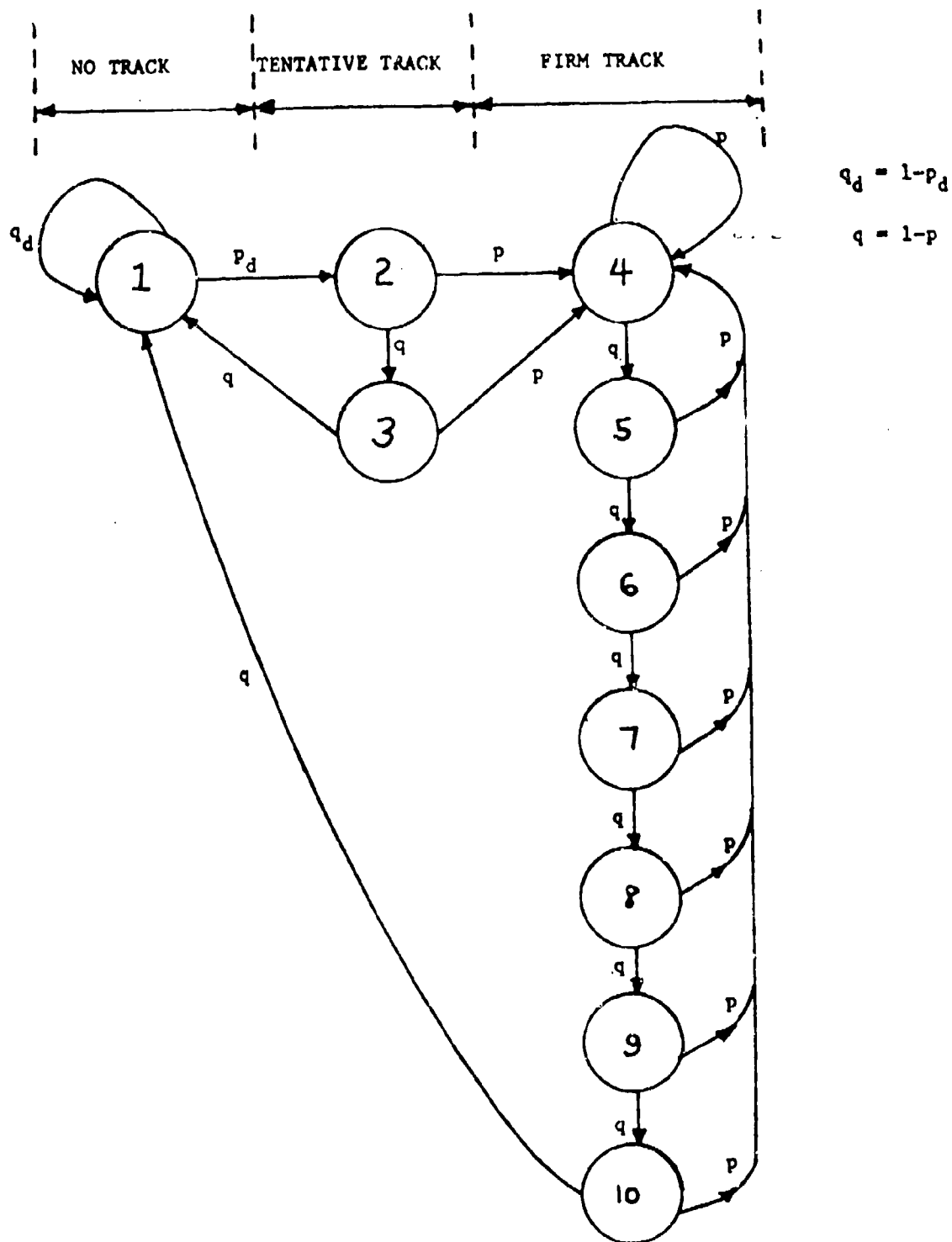


FIGURE B-1 MARKOV STATE DIAGRAM FOR LOGIC A

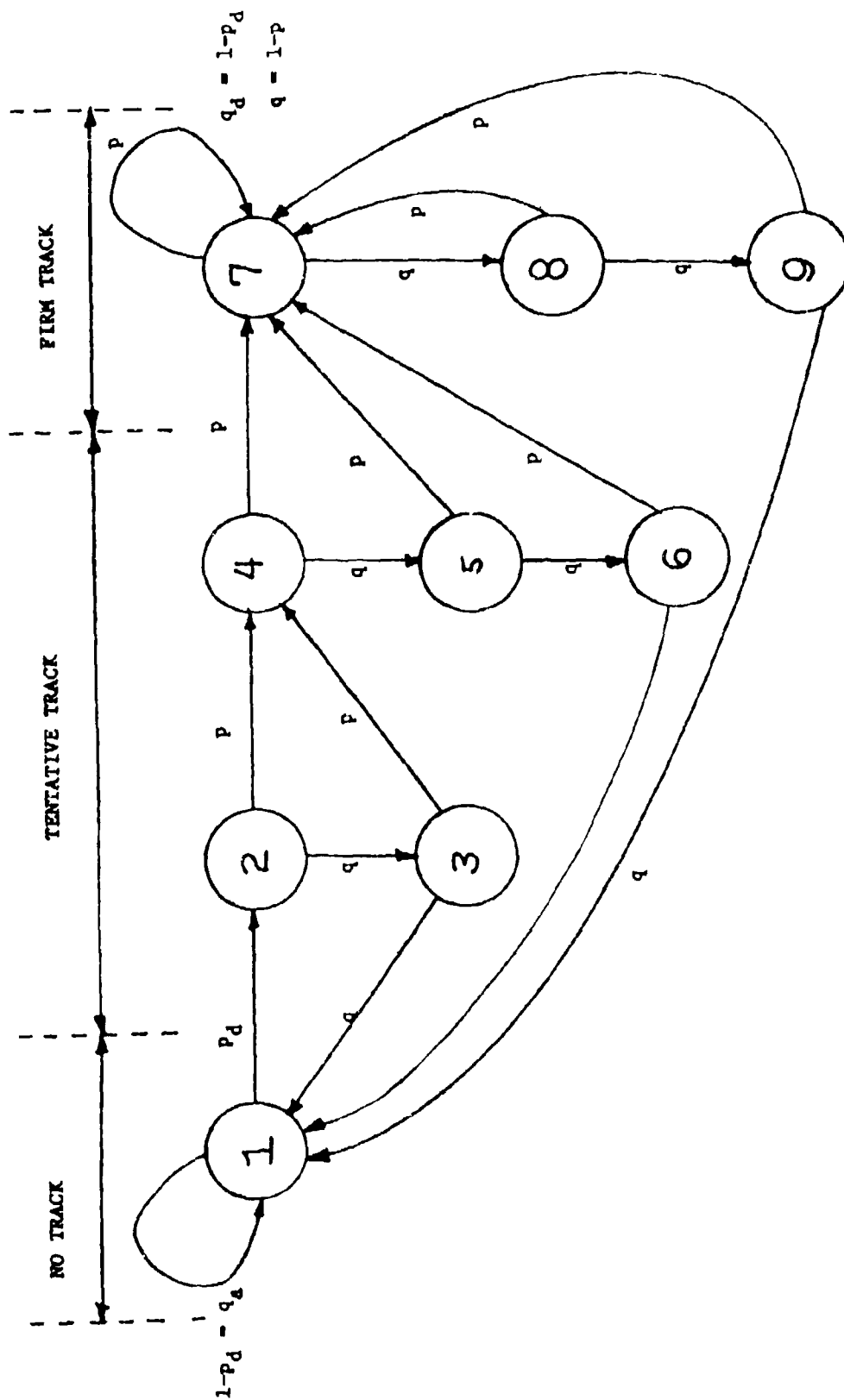


FIGURE B-2 MARKOV STATE DIAGRAM FOR LOGIC B

of state 7. The target is dropped (state 1) only if no data report occurs for three consecutive scans.

Acquisition logics A and B are compared in Figures B-3 and B-4 under the assumption that the probability of detection p_d is equal to the probability of successful correlation p . This will be true when predicted window sizes are large enough so that the target reports have a very small probability of falling outside the predicted window. Also, the predicted windows are assumed to be small enough so that the probability of false reports falling within the gate and correlating with the track is very small. Under these assumptions Figures B-3 and B-4 show the steadystate probabilities of track states as a function of single scan detection probability. It can be seen from these two figures that for $p_d = 0.75$ the probability of firm track is approximately 1 for Logic A and 0.94 for Logic B.

When Logics A and B are analyzed for acquisition delay, or the number of scans required to enter the "firm track" state from the "no track" state, we obtain the following results for probability of detection equal to 0.75 and 0.8:

	<u>A</u>		<u>B</u>	
	<u>$p_d = 0.75$</u>	<u>$p_d = 0.8$</u>	<u>$p_d = 0.75$</u>	<u>$p_d = 0.8$</u>
<u>Acquisition Delay</u>				
Mean (scans)	2.8	2.5	4.1	3.8
Standard Deviation (scans)	1.2	1.0	1.6	1.3

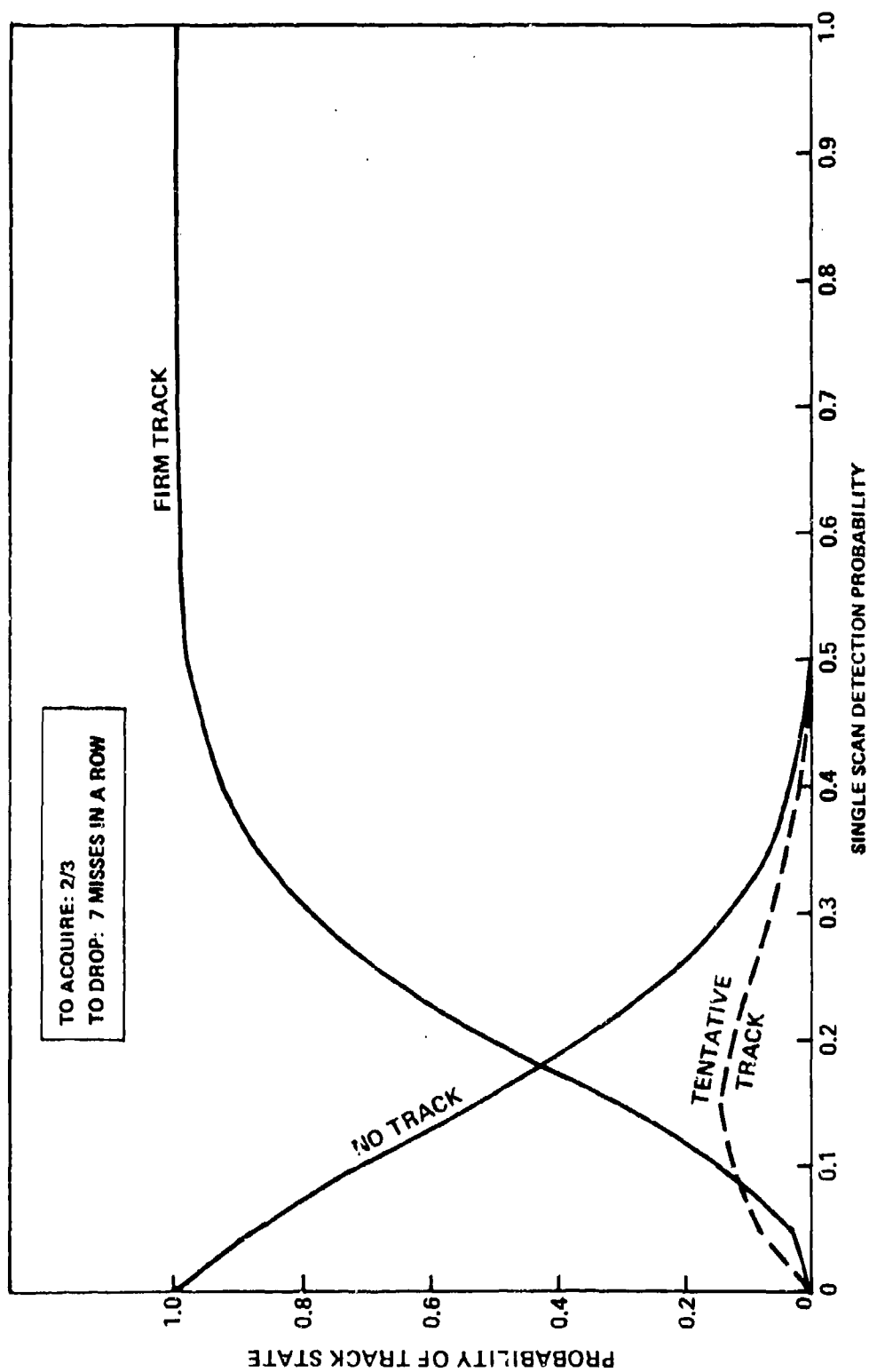


Figure B-3 Steady-State Performance of Logic A

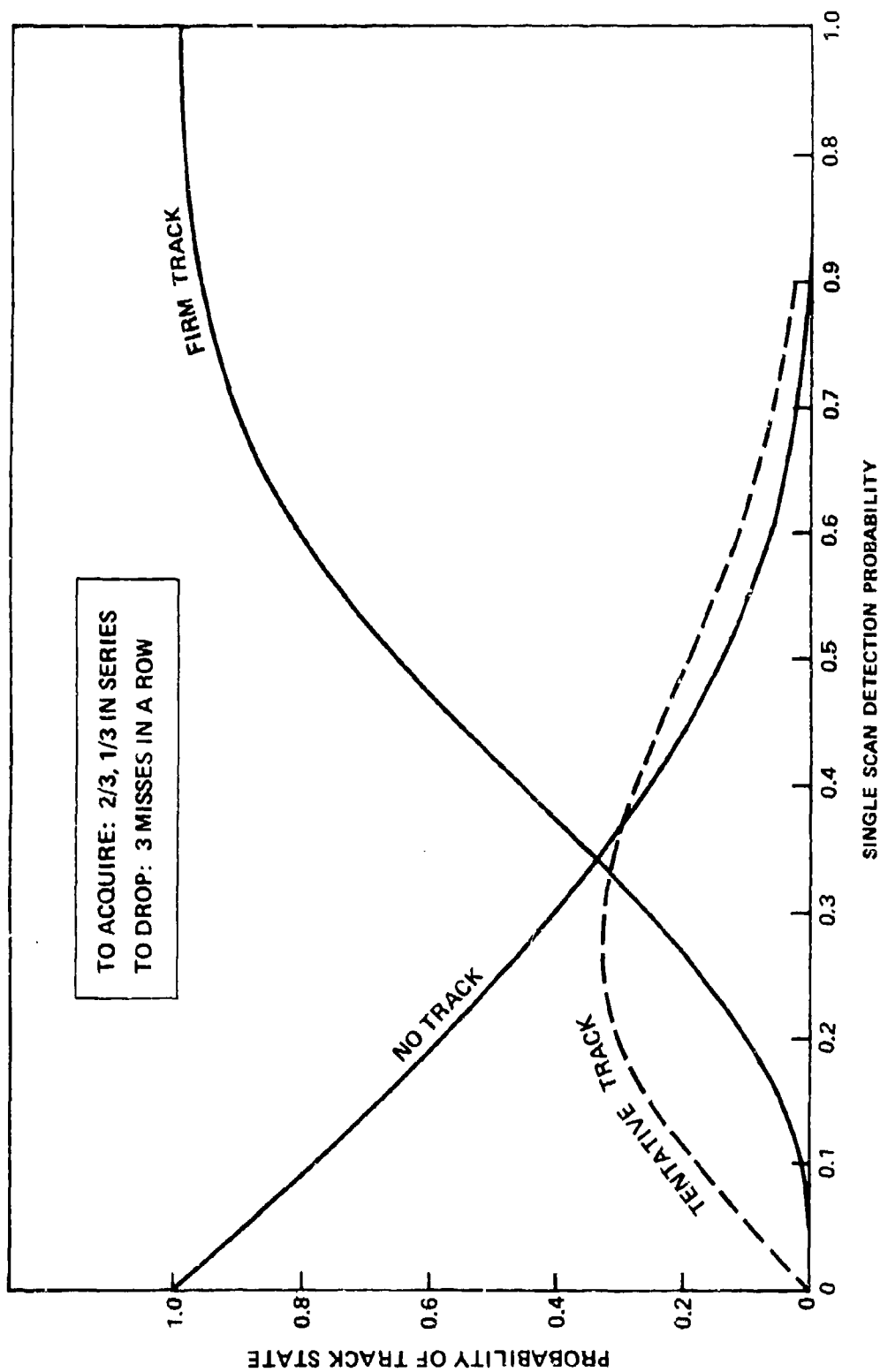


Figure B-4 Steady State Performance of Logic B

APPENDIX C

SIGNAL PROCESSING LOSSES

Explanation of the methods used in calculating the signal processing losses are best explained using examples. Table C-1 shows the results of the calculations which are explained in subsequent sections.

Mechanically scanning antennas with various numbers of pulses per dwell are considered as well as step-scan antennas. Because the radar is to be used in an automated system, we choose processing types which provide a digitized output; namely, the sliding window detector and coherent detection over a group of pulses together with mean-level thresholding. The calculated examples correspond to the cases quoted in the main body of the report.

C.1 Signal-to-Noise Ratio

Before discussing the various processing losses we present in Figure C-1, graphs of single pulse SNR required for various detection probabilities. Results for both steady targets and Swerling Case 1 targets are shown. The Swerling Case 1 target cross section has a slowly varying exponential probability density distribution. This produces a Rayleigh voltage distribution. It stays constant in amplitude during one radar dwell, but varies in amplitude from scan to scan. For the Swerling Case 1, the signal strength on the ordinate of Figure C-1 is that corresponding to the mean cross section of the target. Median cross section value was specified in the requirements section. The mean is 1.6 dB above the median for an exponentially distributed target cross section.

Also shown in Figure C-1 are graphs showing the SNR of two or more looks taken at a target when detection is required on only one to declare the presence of a target. These curves will be used subsequently in estimating losses when range, azimuth or Doppler splitting of the target returns are involved.

TABLE C 1
SIGNAL PROCESSING LOSSES FOR DIFFERENT SYSTEMS

SIGNAL PROCESSING LOSSES FOR DIFFERENT SYSTEMS				
Processing Employed	Sliding Window Detector	Scanning Antenna		Step-Scan Antenna
		Coh. Int. & M.L.T.*	Coh. Int. & M.L.T.*	
<u>System Parameters</u>				
Pulses per Dwell	19	31	23	32
Pulses Processed in a Group	19	10	10	8
SNR ($P_d = 0.75$, $P_{fa} = 10^{-5}$) per Pulse	6.5 dB	6.0 dB	6.0 dB	7.0 dB
<u>Losses</u>				
Sliding Window vs. Non-Coherent	1.3			
Target Median to Mean Ratio	-1.6	-1.6	-1.6	-1.6
Pulse Waveform Mismatch	0.5	0.5	0.5	0.5
Range Gate Straddling	0.8	0.8	0.8	0.8
Doppler Weighting		0.9	0.9	0.9
Doppler Straddling		0.5	0.5	0.5
Azimuth Weighting and Straddling	1.7	-0.3	0.4	-5.9
Threshold Estimation	1.9	1.9	1.9	1.9
IF SNR	11.1 dB	8.7dB	9.4dB	4.1 dB

*M. L. T. = Mean-Level Thresholding

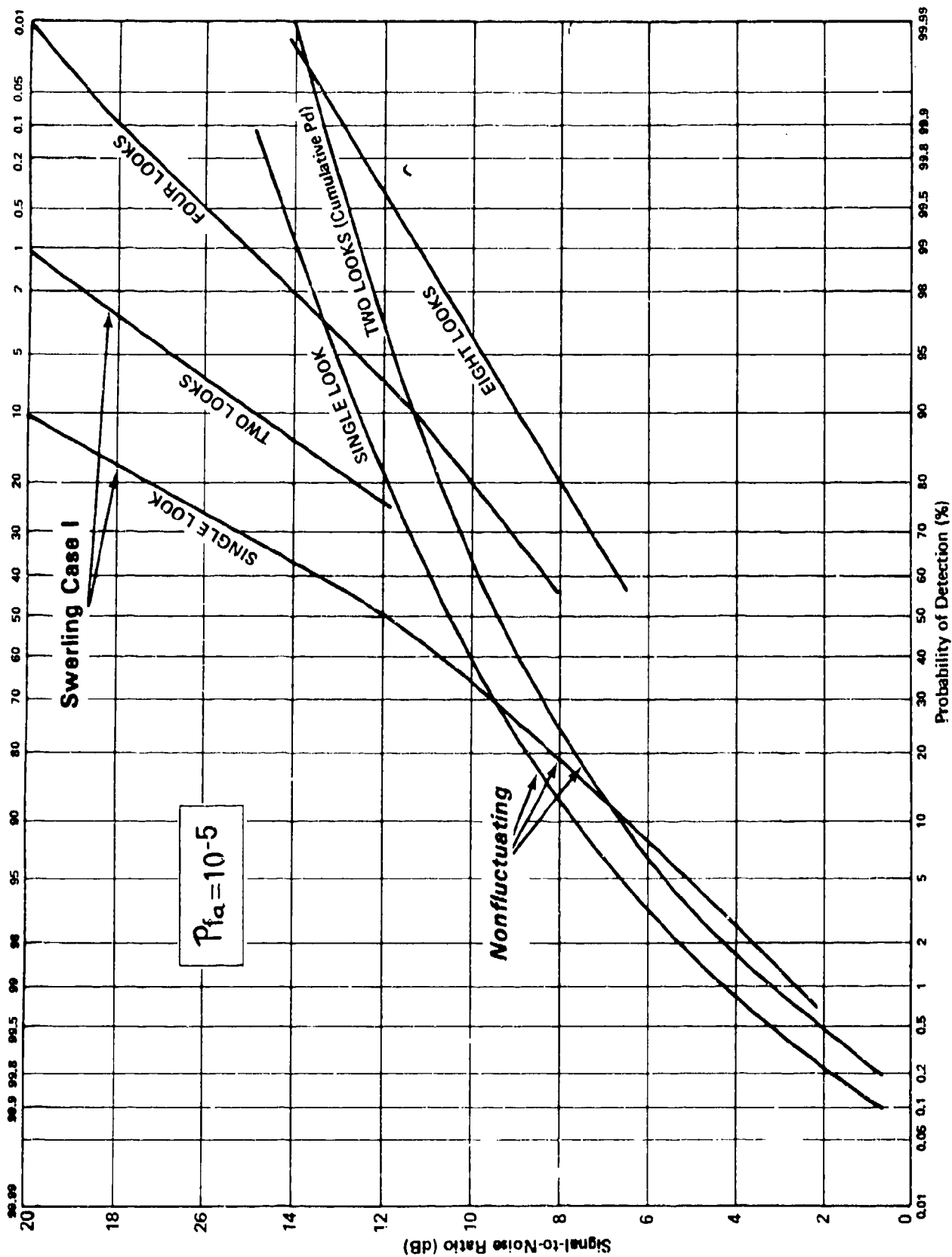


Figure C-1, Single Pulse Signal-to-Noise Ratio vs. Probability of Detection

The SNR for the sliding window detector has been shown to introduce a loss of approximately 1.3 dB over non-coherent integration ⁽¹⁹⁾ when processing 4 to 30 pulses. Thus, for the first column in Table C-1 we use the SNR for non-coherent integration of the appropriate number of pulses and add 1.3 dB for the sliding window detector. This loss can be reduced about 1 dB by using four-level quantization instead of binary quantization.

C.2 Processing Losses

C.2.1 Pulse Waveform Mismatch

The transmitted waveform is almost always a simple rectangular pulse. On receive it is filtered using a filter whose bandwidth is closely related to the reciprocal of the pulse width. The losses for various filters are shown in Skolnik. ^(9, pg. 2-15) A reasonable loss value for a well matched filter is 0.5 dB.

If a coded pulse is used and weighting is used to reduce the time sidelobes, a pulse waveform mismatch will result. For the 13-bit Barker code we assume no weighting and accept the -22 dB sidelobes implied.

C.2.2 Range Gate Straddling

Skolnik ^(9, pgs. 5-26) shows the temporal response of various filters to a rectangular pulse. Range gate sampling will occur at equally spaced points in time. An average should be determined between sampling at the center of the pulse and at points half the sampling interval on either side of the center of the pulse. If one happened to sample at points equally spaced before and after the pulse center, there would be two chances for detection. Since different noise values would obtain at these two points, the detections would be statistically independent and we have the case shown in Figure C-1 of the two looks at a non-fluctuating target.

in our case, a 1 μ sec pulse is used and sampling occurs at 0.75 μ sec intervals. An equally split target return will be sampled ± 0.375 pulse. Skolnik (9, pgs. 5-26) shows a signal reduction of about 3 dB at this point for a reasonable filter shape. But, since we have the possibility of detection on two looks, we find from Figure C-1 that the SNR can be about 1.3 dB less than for a single look. Thus, the range gate straddling loss for even split is about 1.7 dB. If we average over all possible splitting, we will get some value between zero and 1.7 dB. We have estimated the average to be 0.8 dB.

C.2.3 Doppler Weighting

For the coherent integration case, weighting is often used to reduce the Doppler sidebands. This weighting of the input signals also causes an increase in the filter widths letting more noise through. Figure C-2 shows the exact filter shapes for a three-pulse canceller followed by an eight-point FFT with cosine on a pedestal weighting where the cosine is 1/4 of the pedestal. The widths of filters 2,3, and 4 would be 6.4 units wide at the 3 dB points if the 10 pulses used were simply coherently added. They are actually 7.8 units wide, giving a SNR loss of 0.9 dB. The number 1 filter is narrower giving less weighting loss. The number 0 filter was synthesized by adding pulses coherently in groups of five and then noncoherently adding two such groups. It also has no weighting loss.

C.2.4 Doppler Straddling

An added loss occurs because the target may have a Doppler off the peak of any one filter response. Figure C-2 shows that, aside from the cross over between the 0 and 1 filters, the signal suffers a 2.4 dB loss when it is half way between two filter peaks. Again, it must be pointed out that detection can occur in either of two filters, so from Figure C-1 a 1.3 dB advantage is gained from this factor leaving a net 1.1 dB degradation. Now this SNR degradation must be averaged over all target velocities. It varies from 0 to 1.1 dB. An average value is estimated to be 0.5 dB.

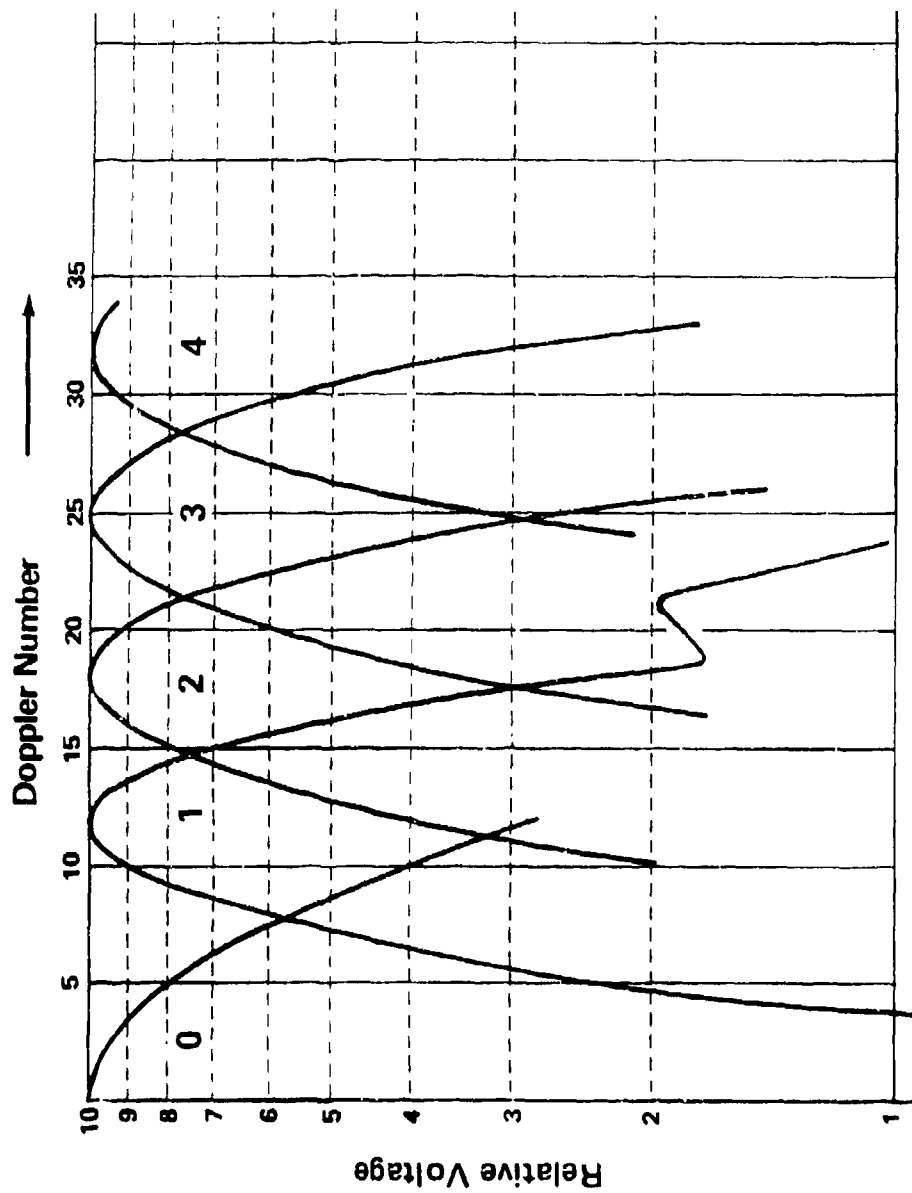


Figure C-2.
Filter Responses of Three-Pulse Canceller Followed by
FFT with Cosine on a Pedestal Weighting

C2.5 Azimuth Weighting and Straddling

For the scanning antenna case the target signal strength varies as the beam scans by. The noise, however, stays constant. All detection calculations so far have been made assuming a constant target at the peak of the beam. To investigate this loss an antenna with a one-way voltage pattern given by:

$$V_1 = \cos\left(\frac{\pi}{2} \frac{\theta}{\theta_b}\right)$$

was assumed. θ_b is the one-way, 3-dB azimuth beamwidth. Since we are concerned here with integration of the voltage returns, we use the two-way voltage pattern.

$$V_2 = \cos^2\left(\frac{\pi\theta}{2\theta_b}\right)$$

Now, consider a group of pulses spanning an angle β , the center of which is offset from the center of the beam by an angle α (See Figure C-3). The normalized voltage sum from this group of pulses would be

$$V_o = \frac{1}{\beta} \int_{\alpha - \frac{\beta}{2}}^{\alpha + \frac{\beta}{2}} V_2 d\theta = \frac{1}{2} + \frac{\theta_b}{\pi\beta} \cos \frac{\pi\alpha}{\theta_b} \sin \frac{\pi\beta}{2\theta_b}$$

The quantity $-20 \log_{10} V_o$ has been plotted for various values of $\frac{\beta}{\theta_b}$ in Figure C-3.

For column 1 in Table C-1, one should balance off the gain caused by non-coherently integrating pulses against the loss caused by scanning of the target by the antenna beam. There must be an optimum number of pulses to process. To obtain an approximate answer to this question, Skolnik's ⁽⁹⁾ data (pgs. 2-22) for SNR required for detection of a Swerling Case 1 target for various number of pulses was combined with data from Figure C-3 for α/β equals zero. It was found that the best number of pulses to integrate is very nearly the number in a one-way 3-dB beamwidth (19 in this case) and the corresponding antenna weighting loss is 1.7 dB.

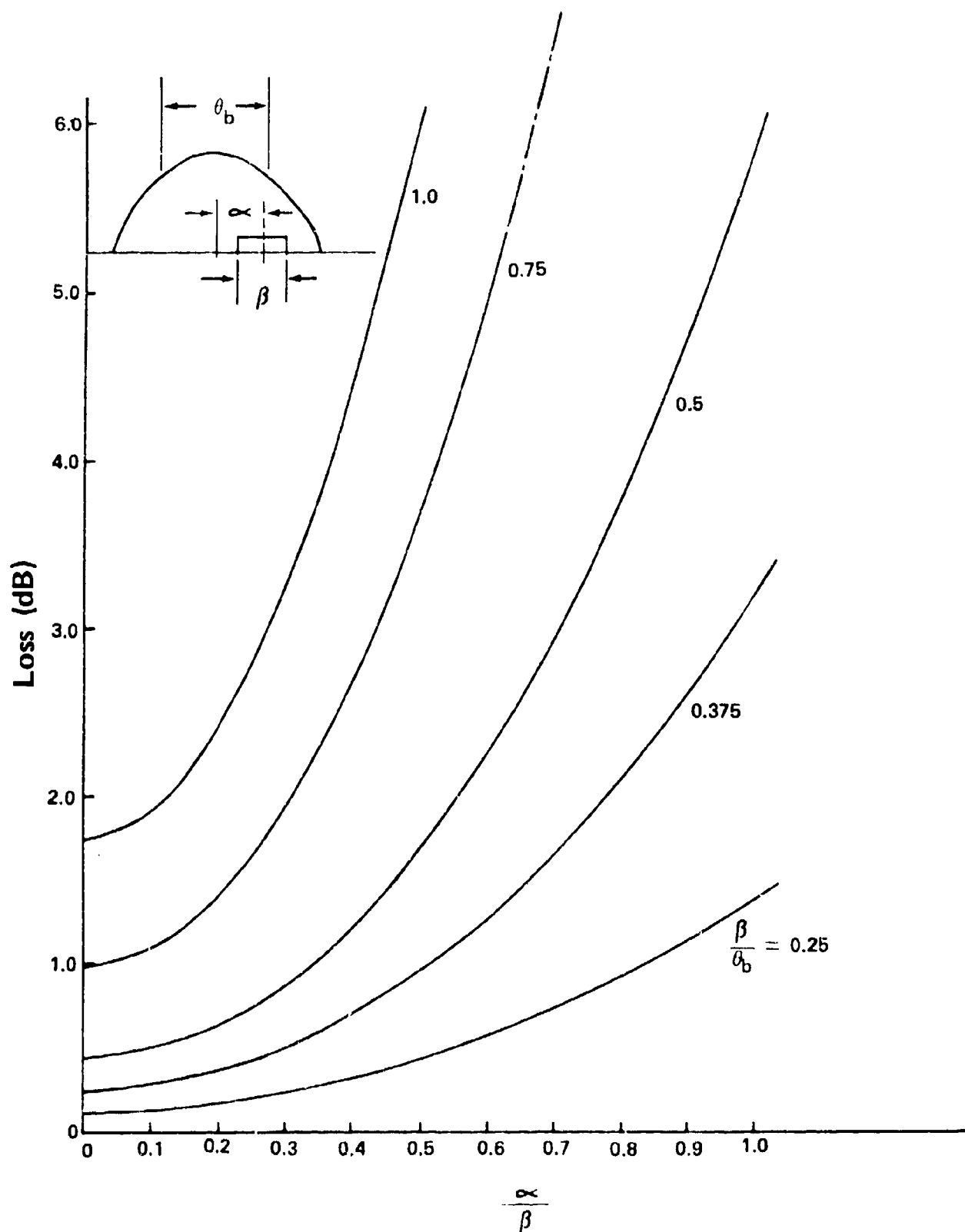


Figure C-3 Loss Due to Azimuth Scanning

Next, to calculate values for column 2 of table C-1, we consider groups of pulses first centered at the beam center and then with $\alpha = \beta/2$. The quantity $\beta/\theta_b = 10/31$ for the second column. A centered group of pulses would experience 0.2 dB loss and there would exist other groups of pulses at $\alpha = \pm \beta$. These groups would experience about 2.8 dB loss. If the center group had a $P_d = 0.75$, then two groups about 2.6 dB lower in strength would (Figure C-1) have a combined $P_d = 0.35$. The cumulative detection probability on these three groups of pulses would be 0.8375, giving a gain of 0.5 dB over the detecting on a single group centered. The net gain is 0.3 dB.

Now, for two pulses at $\alpha = \pm \beta/2$, the loss from Figure C-3 is 0.9dB, but since two looks are involved, a gain of 1.3 dB is obtained (see Figure C-1) for a net gain of 0.4 dB.

The average net gain is then 0.3 dB. This is entered as a negative loss in Figure C-1 column 2. For column 3, $\beta/\theta_b = 10/23$ and a net average loss of 0.4 dB occurs.

For the step-scan case in column 4, there is no weighting loss since the antenna is not scanning. The beamwidth is 2.4 deg, and the beams are spaced 1.875 deg apart so that the two-way loss at the cross over points is 3.5 dB. Since we are only using eight pulses in a processing group, it makes sense to space the looks so that they are as far apart in space and time as possible. For a target at the center of a beam, it is better to look four times, one second apart giving a gain of 6.8 dB (compare single look and four looks for Swerling Case 1 in Figure C-1) than to non-coherently integrate the results of processing four groups giving only 4.5 dB gain. In like manner, adjacent beams should be excited as far apart in time as possible to give the target signal a chance to decorrelate. The scanning schedule for the electronically step-scanned cylindrical array is to transmit eight pulses on the odd-numbered beams in succession and then transmit pulses on even-numbered beams. Repeat this once per second. In the normal four-second scan time, beam-centered targets will be looked for four times with a net gain of 6.8 dB (after subtracting the two-way antenna gain). The average gain is then 5.9 dB which is entered as a negative loss in column 4.

C.2.6 Threshold Estimation

There is some loss in setting the thresholds. Typically, samples of the expected noise or clutter level are collected from nearby range cells or from the same range-azimuth cell over a period of time. These are averaged to find the mean. This mean is multiplied by a constant "a" in Figure C-4 to establish the threshold. Because a finite number of clutter samples are taken, the threshold estimate has some inaccuracy and as a consequence, the constant multiplier "a" must be set higher, the fewer the number of samples. We will assume that 15 samples are used. At the 10^{-5} false alarm level, the ratio of "a" for 15 samples to that for an infinite number (perfect knowledge of noise or clutter background) is 1.9 dB.

C.3 IF Signal-to-Noise Ratio

Finally, the various columns are added in Table C-1 to include all of the processing losses with the SNR per pulse to obtain the IF SNR per pulse. These are entered in Table 3-1 in the body of the report.

It is interesting to note the difference in required IF SNR for a radar employing a sliding window detector and an equivalent radar employing coherent integration over 10 pulses plus mean level threshold. The latter requires 1.7 dB less SNR for the same detection characteristics.

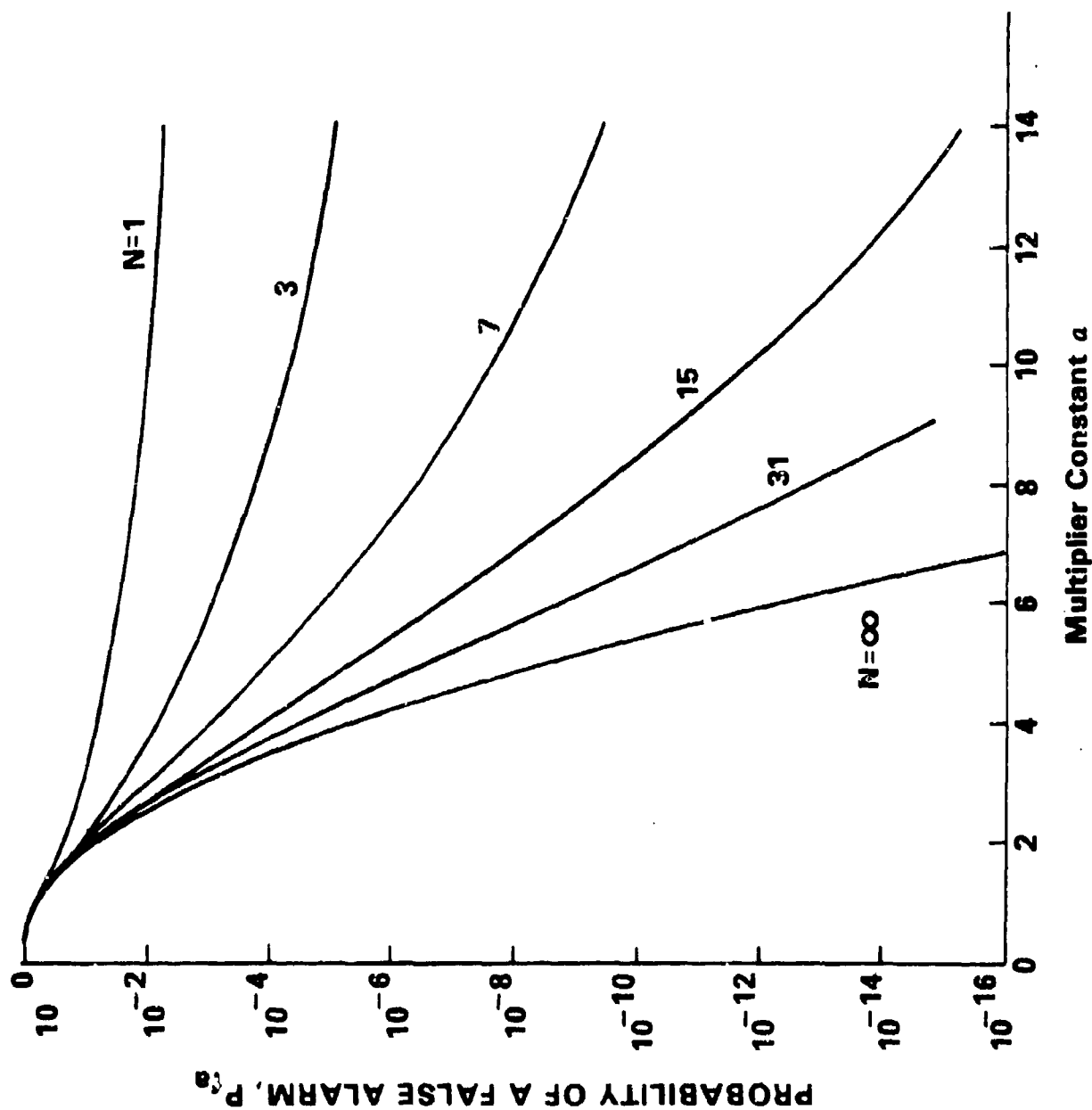


Figure C-4 Probability of False Alarm as a Function of Multiplying Factor for a Mean-Level Threshold Estimated using N Samples

APPENDIX D

ENVIRONMENTAL DATA

The principal environmental factors with which the radar must contend are: ground clutter, weather clutter, bird flocks (angels), ground vehicles, and interference from other radars in the same frequency band. In addition, anomalous propagation often aggravates the clutter situation. This Appendix discusses the nature of each of these environmental factors as they affect the radar's performance.

D.1 Ground Clutter

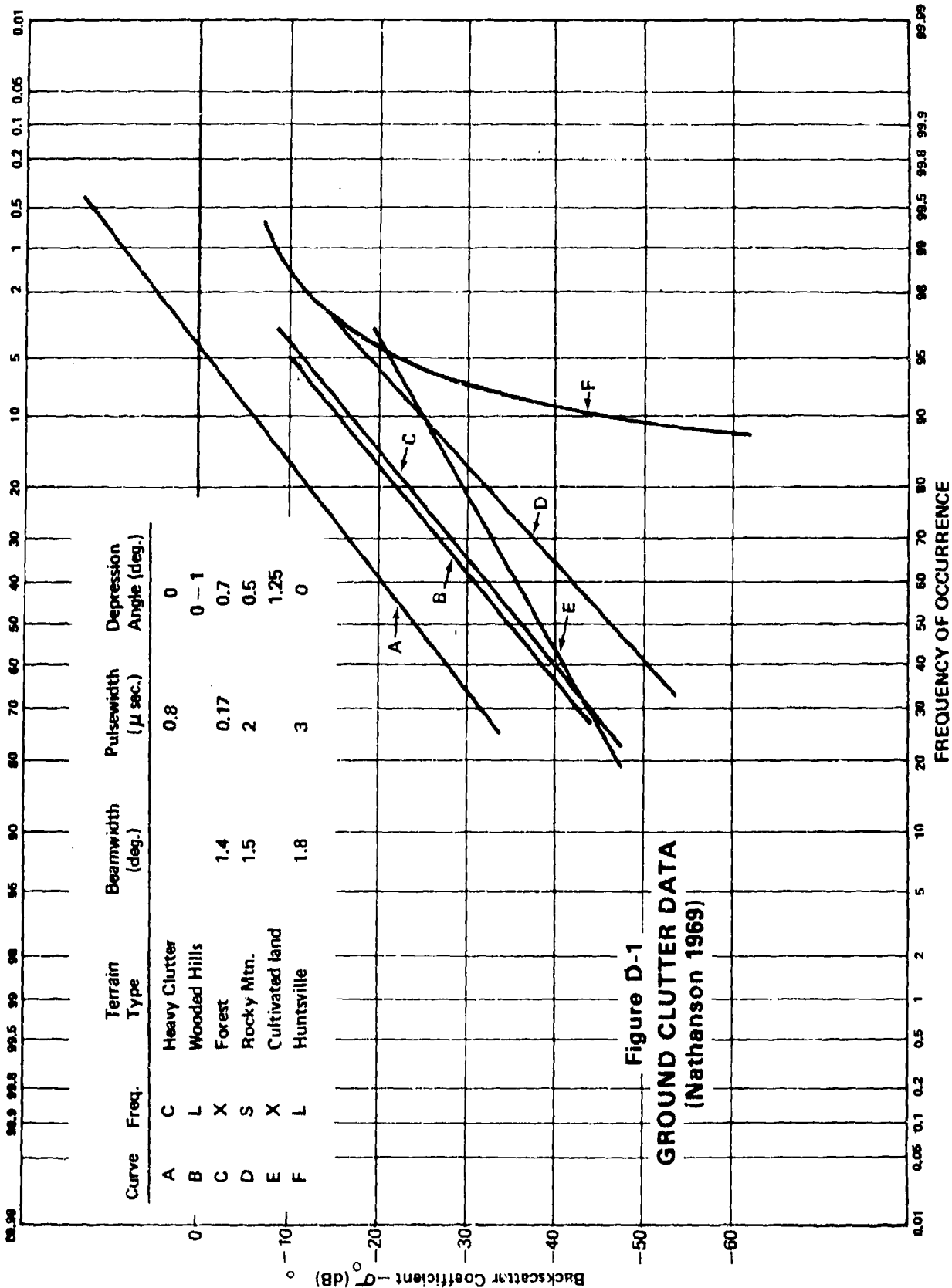
Ground clutter returns may be divided into three regimes:

(a) Strong returns are experienced from large, generally man-made objects. These are called discretely. Measurements indicate that many discretely have cross sections of 10^4 to 10^6 m² or more at S-band. In one set of measurements ⁽²⁰⁾ near a large city, there were about 110 discretely above 10^4 m² cross section. Most were identified as man-made objects. The size of the return from a discrete is usually independent of the range resolution employed.

(b) The ground in a large percent of the radar's resolution cells is in shadow and returns no clutter signal, only noise. The boundary between clutter and shadow is usually quite sharp. Using a ground clutter map, it is possible to see aircraft with good probability of detection in these clutter-free regions.

(c) The remaining clutter cells generally contain an assemblage of smaller reflections. Their returns add differently on each scan, but are characterized by a mean σ_0 . From cell to cell, σ_0 varies usually with a distribution close to log-normal.

Figure D-1 shows data from several sources as reported by Nathanson ⁽⁸⁾ We see that if a radar is designed to see up to $\sigma_0 = -15$ dB, it will see aircraft in between 75 and 97% of the resolution cells depending on which clutter condition applies. The radar should be designed so that clutter levels much larger than -15 dB will not cause an excessive number of false alarms.



D.2 Precipitation Clutter

The instantaneous frequency of occurrence of various rainfall rates ⁽²¹⁾ for various parts of the U.S. are shown in Figure D-2. The equation for calculating the volume of backscatter coefficient η is also shown in the figure.

The radar should be designed to see most aircraft in the presence of a heavy rain (16 mm/hr) which is found only 0.3% of the time.

The rain spectrum is determined by wind conditions ⁽⁸⁾. Rain returns will typically have a spectral width of about 25 knots due to difference in wind velocity with altitude. The mean velocity will vary over wide values depending on the wind speed and the viewing angle of the radar with respect to the wind velocity vector. Simple MTI cancellers only reject the rain near zero radial component of velocity letting most pass through. Circular polarization reduces rain returns about 15 dB while reducing target strength 2 to 5 dB. It is clear that at the higher frequencies some other form of filtering is required to reduce rain clutter to a tolerable level.

D.3 Bird Flocks (Angels)

A typical distribution of angel cross section is shown in Figure 3-12. Bird ground speeds range between 0 and 80 knots. They generally fly at altitudes between 1,000 and 6,000 ft.

An R^{-4} STC attenuation law has been found to work very well ^(2,22) in eliminating most angels. Those angels which are at the peak of the elevation beam are found to be most troublesome. The range extent of most angels is limited to that range at which the peak of the elevation pattern crosses the bird's altitude.

Birds are definitely a problem, especially during the spring and fall migrating seasons, for S-and L-band radars. Very little data is available for UHF radars where it seems certain that flocks of larger size birds should cause trouble ⁽²³⁾.

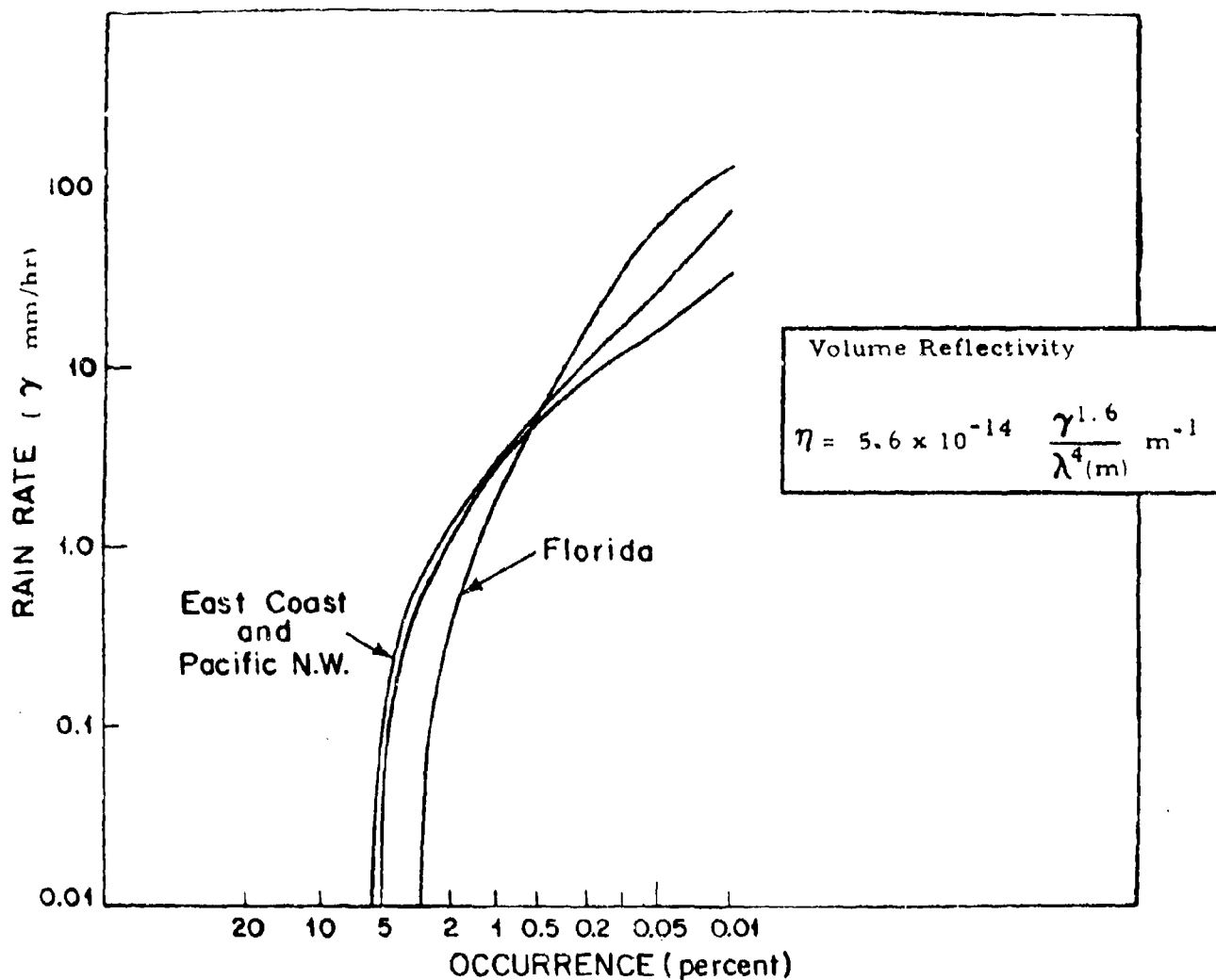


Figure D-2
 CUMULATIVE DISTRIBUTION OF INSTANTANEOUS RAINFALL RATES
 ASR PERFORMANCE LIMITATION AGAINST LOW FLYING AIRCRAFT

D.4 Ground Vehicles

The cross section of ground vehicles is in the same range as aircraft cross sections (1 to 100 m²). Their velocities allow them to be seen at the output of the usual Doppler filters employed.

Usually, only short sections of roads are visible to an ASR so that ground vehicle returns may or may not start a false aircraft track. It appears that the best way to eliminate ground vehicle returns is to teach the scan-to-scan correlator where these vehicles are likely to appear and what are their likely radial velocities. The correlator can then recognize and eliminate any target detections caused by ground vehicles.

D.5 Interference

The most common type of interference experienced by an ASR is from other pulsed radars in the same frequency band. Beyond about 40 nmi these signals are propagated by tropospheric scatter (9, Chapt. 29)

and are emphasized when anomalous propagation conditions exist.

Radars operating on the same frequency must be hundreds of miles apart to completely avoid any interference problems. There are, however, existing pulse interference suppression techniques which allow same-frequency operation at much closer ranges.

Two of these techniques are:

(1) The video is limited and then non-coherently integrated from pulse to pulse. The limiting greatly reduces the pulse interference contributed to the integrated sum. A double threshold (moving window) detector operates to eliminate pulse interference in the same manner.

(2) Where coherent integration over many pulses is employed, the group of pulses to be integrated can be examined for the existence of a pulse significantly larger than the mean. If one exists, detection in the cell can be censored. This technique has been found to completely eliminate pulse interference in the MTD radar presently being tested at NAPEC.

Using the pulse interference eliminating techniques just described, radars can be operated on the same frequency only when tens of miles apart. Several thousand could be operated in a 50-MHz bandwidth within the continental U.S.

APPENDIX E

TRANSMITTER TUBE AVAILABILITY

Tables E-1 through E-4 list the key parameters of pulsed power amplifier tubes for the four frequency bands of interest. Magnetrons are excluded because of the requirement for coherent waveforms to cancel second-time-around clutter.

Both klystrons and traveling wave tubes are suitable for the ASR() coherency requirements. Traveling wave tubes have the very desirable feature that they are broadband amplifiers and do not require tuning as most klystrons do. The twystron (Table E-1 is a hybrid tube consisting of klystron and traveling wave tube stages; broadband operation is achieved, but these tubes operate well only at relatively high peak power levels (above 2-4 MW). Cross-field amplifiers are also broadband devices but their low gain (8-13 dB) necessitates are of a multi-stage transmitter.

Selection of a suitable transmitter tube is one of the most crucial aspects of system design. Risk is minimized by using an existing design where possible; this is also advantageous because reliability and operating life data can be obtained from previous users of the tube. When no existing design is available, successful tubes operating at different frequencies can often be scaled to the desired frequency band, but this requires evaluation of several test models of the new tube and the risk of having poor reliability and life is high until sufficient field experience is gained with the new design.

TABLE E-1
S_L-BAND PULSED POWER AMPLIFIER TUBES

2.7-2.9 GHz, 200 kW to 5 MW Peak Power

<u>Tube</u>	<u>Type</u>	<u>Frequency</u>	<u>Peak Power</u>	<u>Average Power</u>	<u>Gain</u>	<u>Tuning</u>	<u>Cooling</u>	<u>Magnet</u>
VA 820	Kly-4	2.7-2.9 GHz	5 MW	10 kW	47 dB	fixed	liquid	solenoid
VA 87	Kly-4	2.7-2.9 GHz	2 MW	2 kW	60 dB	mech.	liquid	solenoid
VA 87E	Kly-5	2.7-2.9 GHz	2 MW	3.5 kW	50 dB	mech.	air	solenoid
TV 2013	Kly	2.7-3.1 GHz	4 MW	60 kW	50 dB	----	liquid	----
VA 839	Kly-6	2.7-2.9 GHz	5 MW	12.5 kW	--	----	liquid	solenoid
VA 145D	Twystron	2.7-2.9 GHz	5 MW	10 kW	--	broadband	liquid	solenoid
VA 145H	Twystron	2.7-2.9 GHz	3 MW	6 kW	36 dB	broadband	liquid	solenoid
VA 145UL	Twystron	2.72-2.92 GHz	3.5 MW	7 kW	36 dB	broadband	liquid	solenoid
TPM 1236	CFA	2.7-3.0 GHz	0.5 MW	4 kW	17 dB	----	liquid	solenoid
L 5373	CFA	2.7-3.5	0.5 MW	1 kW	13 dB	broadband	liquid	electro
L 5332	CFA	2.7-3.5	0.5 MW	2.5 kW	16 dB	broadband	liquid	electro

Kly-N = N-cavity klystron

CFA = Crossed Field Amplifier

Twystron = TWT/Klystron hybrid

TABLE E-2
L-BAND PULSED POWER AMPLIFIER TUBES
1.25 - 1.35 GHz, 100 kW - 1 MW Peak Power

<u>Tube</u>	<u>Type</u>	<u>Frequency</u>	<u>Peak Power</u>	<u>Average Power</u>	<u>Gain</u>	<u>Tuning</u>	<u>Cooling</u>	<u>Magnet</u>
L3486	Kly	1.25 - 1.38 GHz	250 kW	17 kW	30 dB	mech.	---	electro
L3739	Kly	1.26 - 1.32 GHz	200 kW	50 kW	30 dB	mech.	---	---
L5494	Kly	1.25 - 1.35 GHz	250 kW	1.8 kW	46 dB	mech.	---	---
L5548	Kly-5	1.25 - 1.35 GHz	300 kW	1.8 kW	36 dB	mech.	air	---
PT1024	Kly-4	1.2 - 1.4 GHz	100 kW	6.2 kW	47 dB	mech.	liquid	electro
VA838B	Kly-5	1.25 - 1.35 GHz	350 kW	17.5 kW	50 dB	mech.	liquid	electro
L5235	ESFK	1.3 - 1.4 GHz	300 kW	4.5 kW	47 dB	mech.	---	none
L5237	ESFK	1.3 - 1.4 GHz	300 kW	2.1 kW	47 dB	mech.	---	none
QKS1319	CFA	1.25 - 1.35 GHz	100 kW	3 kW	13 dB	broadband	liquid	permanent
QKW1671	TWT	1.15 - 1.40 GHz	160 kW	9 kW	50 dB	broadband	liquid	permanent
QKW1518	TWT	1.15 - 1.40 GHz	160 kW	9 kW	50 dB	broadband	liquid	permanent
QKW1723	TWT	1.175 - 1.425 GHz	175 kW	10 kW	45 dB	broadband	liquid	electro
QKW1701	TWT	1.2-1.4 GHz	300 kW	10 kW	50 dB	broadband	liquid	electro
QKW1722	TWT	1.215-1.40 GHz	160 kW	10 kW	50 dB	broadband	liquid	electro

Kly - N = N-cavity klystron
 ESFK = Electrostatically-focused Klystron
 CFA = Crossed Field Amplifier
 TWT = Traveling Wave Tube

TABLE E-3
S_H-BAND PULSED POWER AMPLIFIER TUBES

3.4 - 3.6 GHz

<u>Tube</u>	<u>Type</u>	<u>Frequency</u>	<u>Peak Power</u>	<u>Average Power</u>	<u>Gain</u>	<u>Tuning</u>	<u>Cooling</u>	<u>Magnet</u>
VA816J	Kly-7	3.4 - 3.6 GHz	3.5 MW	3.6 kW	35 dB	mech.	liquid	electro

TABLE E-4
UHF-BAND PULSED POWER AMPLIFIER TUBES

0.4 - 0.45 GHz

<u>Tube</u>	<u>Type</u>	<u>Frequency</u>	<u>Peak Power</u>	<u>Average Power</u>	<u>Gain</u>	<u>Tuning</u>	<u>Cooling</u>	<u>Magnet</u>
3KM 3000 LA	Kly-3	0.4-0.45 GHz	12 kW	7.2 kW	31 dB	mech.	air	electro
VA842	Kly-4	0.4 - 0.45 GHz	1.3 MW	75 kW	41 dB	mech.	air/liq.	electro
VA X 602K	Kly-4	0.375-0.5 GHz	150 kW	33 kW	45 dB	---	---	electro
QKW1630	TWT	0.4 - 0.5 GHz	250 kW	16 kW	40 dB	broadband	liquid	permanent
SFD-225	CFA	0.405-.45 GHz	250 kW	7.5 kW	10 dB	broadband	air	electro
NO8SR-91370	CFA	0.406-.45 GHz	250 kW	7.5 kW	10 dB	broadband	air	permanent
I1004	CAV	0.41-0.46 GHz	14 kW	2.1 kW	--	--	--	--
3045	CAV	0.42	35 kW	70 kW	--	--	--	--

Kly-N = N-cavity Klystron

CFA = Crossed Field Amplifier

TWT = Traveling Wave Tube

CAV = Cavity-type

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